# EFFECTS OF SUB-OPTIMAL COMPONENT PERFORMANCE ON OVERALL COOLING SYSTEM ENERGY CONSUMPTION AND EFFICIENCY

A Thesis
Presented to
The Academic Faculty

by

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In Partial Fulfillment
of the Requirements for the Degree
Doctor of Philosophy in the
School of Architecture

Georgia Institute of Technology
May 2012

# EFFECTS OF SUB-OPTIMAL COMPONENT PERFORMANCE ON OVERALL COOLING SYSTEM ENERGY CONSUMPTION AND EFFICIENCY

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Date Approved: March 12, 2012

To the memory of my beloved father

Also

to my lovely patient mother, my brilliant brother,

and

my beautiful talented wife

## ACKNOWLEDGEMENTS

I would like to especially thank my mentor and advisor Professor Godfried Augenbroe, without his guidance and support I would not be here.

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# LIST OF SYMBOLS AND ABBREVIATIONS

ANSI American National Standards Institute

AHRI (ARI) Air-Conditioning, Heating and Refrigeration Institute

ASHRAE American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

ASTM American Society for Testing and Materials

bhp Brake horsepower

Btu/h British thermal unit per hours

CFM Cubic feet per minute

COP Coefficient of performance

CTI Cooling Technology Institute

DB Dry bulb

DDC Direct digital control

DOE U.S. Department of Energy

EAT Entering air temperature

ECaE Energy Consumption and Efficiency

EER Energy efficiency ration

EWT Entering water temperature

F Fahrenheit

FPM Feet per minute

ft foot

GPM Gallons per minute

h hour

hp horsepower

| | |
|---|---|
| IES | Illuminating Engineering Society of North America |
| in. | inch |
| K | Kelvin |
| KW | Kilowatts |
| LAT | Leaving air temperature |
| LWT | Leaving water temperature |
| L/S | Liters per second |
| M/S | Meters per second |
| OA | Outside air |
| Pa | Pascal |
| RA | Return air |
| rpm | revolutions per minute |
| SA | Supply air |
| SC | Shading coefficient |
| SHGC | Solar heat gain coefficient |
| T | Temperature |
| Tons | Tons of refrigeration (12000 Btuh) |
| VAV | Variable air volume |
| VFD | Variable frequency drive |
| W | Watt |
| WB | Wet bulb |

# DEFENITIONS

Aleatory uncertainties**:** Aleatory or stochastic uncertainty is a type of unpredicted and irreducible uncertainty that can be created because of random behavior of a physical system, such as non-considered swings in environment conditions.

A posteriori: It is an inductive logic based on solid facts, or search first and then decide.

A priori: It is a deductive logic which start with the decision before the search of the solution space.

Baseline building design: Baseline building design is a computer representation of an imaginary design which is set up based on the proposed design building project. This representation is used as the basis for comparing the baseline performance for rating the quality of the designed building.

Baseline building performance: Baseline building performance is the annual energy cost for a building design intended for use as a baseline for rating the quality of the designed building.

Bin Size: Number of occurrences in an interval during a sampling base simulation.

Budget building design: Budget building design is a computer representation of an imaginary design based on the actual proposed building design. This representation is used as the basis for calculating the energy cost budget.

Coefficient of performance (COP): the ration of the rate of heat removal to the rate of energy input, in consistent units, for a complete refrigerating system.

Control: Control is regulating of the operation of an equipment.

Control device: A control device is a specific device that is used to regulate the operation of an equipment.

Construction document: Construction document is a set of drawings and specifications that are used to construct a building or a building system.

Cooling design temperature: Cooling design temperature is the outdoor dry bulb temperature that is equal to a temperature that is exceeded by 1% of the number of hours during a typical weather year.

Design capacity: Design capacity is the output capacity of a system at design conditions.

Design conditions: Design condition is the specific environmental conditions, such as temperature, that is required to be provided and kept by a system and under that the system have to operate.

Direct digital control (DDC): Direct digital control is a type of control where controlled and monitored analog or binary data are converted to digital format for manipulation and calculation by a digital computer, and then converted back to analog or binary form to control physical devices.

Ductwork: Ductwork is a system of ducts that helps distribute or extract air to/ from a space.

Efficiency: Efficiency is the performance at a specific rating condition.

Energy: Energy is the capacity for doing work, measured in British thermal units (Btu)

Energy efficiency ratio (EER): Energy efficiency ratio is the ration of net cooling capacity in Btu/h to total rate of electric input in watts under design operating conditions.

Energy Service Company (ESCo): ESC companies guaranty the performance of the buildings for as many as 10 to 15 years.

Epistemic uncertainties: Epistemic uncertainty can be created because of lack of knowledge or inadequate information such as lack of reliable data.

Equipment: Equipment is a set of devices for providing comfort conditioning, such as air conditioners and chillers.

Fan brake horsepower (bhp): Fan brake horsepower is the horsepower delivered to the fan's shaft. Brake horsepower does include the mechanical drive (belts, etc.) losses.

Fenestration: Fenestration is all areas in the building envelope that allow light to enter the space (e.g. windows, skylights, etc.)

Global methods: In global methods all the variables are sampled in the same time, and the uncertainty in a specific input parameter is used to determine the uncertainty in the output.

Histogram: The histogram compares the frequency of the results with the outcome itself.

Humidistat: Humidistat is an automatic control sensor that is used to measure the humidity in the space.

HVAC system: HVAC is a set of equipment, distribution systems and terminals that provide heating, ventilating and air conditioning of the building.

Integrated part-load value (IPLV): IPLV is a number that expresses part-load efficiency of an air conditioning equipment on the basis of weighted operation at various load capacities for the equipment.

Kilowatt (KW): KW is a unit of electric power, equal to 1000 watts.

Latin hypercube sampling (LHS): The LHS is a specific type of sampling which provides a good coverage of the sample space of the inputs.

Local methods: When the correlation between inputs and outputs is linear a local method can provide information about the individual uncertainty.

Manufacturer: Manufacturer is a company that is engaged in the original production and assembly of products or equipment.

Mean deviation $\mu$: The mean deviation is the expected value of a random variable.

Nameplate rating: Nameplate rating is the design load operating condition of an equipment as it is shown by the manufacturer on the nameplate.

Normal distribution: In a normal distribution or Gaussian distribution the probability density function is defined by the mean deviation, $\mu$ and the standard deviation squared, $\sigma^2$.

One factor at a time (OAT) method: OAT is a sampling procedure that varies only one factor at a time.

Outdoor (outside) air: Outdoor is the air that is outside of the building envelope.

Parameter screening/ reduction: Parameter screening is the reduction of parameters to most important parameter in order to simplify the procedure of Uncertainty and sensitivity analysis.

Regression analysis: The regression analysis provides additional quantitative insight into the results of a sensitivity analysis.

Sampling based methods: This method is based on conducting repeatedly sampling from a known distribution.

Sensitivity analysis: The sensitivity analysis (SA) provides insight into the relative degree of importance or contribution of individual input variable to the uncertainty of the output results in an uncertainty analysis.

Shading coefficient (SC): Shading coefficient is the ratio of solar heat gain at normal incidence through glazing to that occurring through 1/8 inch thick clear, double-strength glass.

Solar heat gain coefficient (SHGC): SHGC is the ratio of the solar heat gain entering the space through the fenestration area to the incident solar radiation.

Standard deviation $\sigma$: The standard deviation is a representative of the variability in a set of given data. As the standard deviation becomes larger, the data set spread will be larger as well.

System: System is a combination of equipment and auxiliary devices such as controls by which energy is transformed so it performs a specific function such as HVAC.

Terminal: Terminal is a device that energy from a system is finally delivered to the space.

Thermostat: Thermostat is an automatic control device that is used to control and monitor the space temperature.

U-factor (thermal transmittance): U-factor is heat transmission in unit time through unit area of a material or construction and the boundary air films, induced by unit temperature difference between the environments on each side in Btu/h.ft2.F.

Uncertainty analysis: Uncertainty analysis (UA) presents the uncertainty in model prediction of output, based on estimated values of inputs to the model.

# SUMMARY

Predicted cooling system performance plays an important role in choices among alternative system selections and designs. When system performance is expressed in proper indicators such as “overall system energy consumption” or “overall system efficiency”, it can provide the decision makers with a quantitative measure of the extent to which a cooling system satisfies the system design requirements and objectives. Predictions of cooling system energy consumption and efficiency imply assumptions about component performance. Quantitative appraisal of the uncertainty (lack of knowledge) in these assumptions can be used by design practitioners to select and design systems, by energy contractors to guarantee future system energy cost savings, and codes and standards officials to set proper goals to conserve energy.

Our lack of knowledge has different sources, notably unknown tolerances in equipment nameplate data, and unpredictable load profiles. Both cause systems to under-perform current predictions, and as a result decrease the accuracy of the outcomes of energy simulations that commonly are used to verify system performance during the design and construction stages. There can be many other causes of unpredictable system behavior, for example due to bad workmanship in the installation, occurrence of faults in the operation of certain system parts, deterioration over time and other. These uncertainties are typically much harder to quantify and their propagation into the calculated energy consumption is much harder to accomplish. In this thesis, these categories of failures are

not considered, i.e. the treatment is limited to component tolerances and load variability. In this research the effects of equipment nameplate tolerances and cooling load profile variability on the overall energy consumption and efficiency of commonly used commercial cooling systems are quantified. The main target of this thesis is to present a methodology for calculating the chances that a specific cooling system could deviate from a certain efficiency level by a certain margin, and use these results to guide practitioners and energy performance contractors to select, and guarantee system performances more realistically. By doing that, the plan is to establish a systematic approach of developing expressions of risk, in commercial cooling system consumption and efficiency calculations, and thus to advocate the use of expressions of risk as design targets.

This thesis makes a contribution to improving our fundamental understanding of performance risk in selecting and sizing certain HVAC design concepts.

# CHAPTER 1

# INTRODUCTION

According to the 2003 Commercial Building Energy Consumption Survey (CBECS), office buildings in the United States comprise roughly 12 billion square foot (1.1 billion square meter) of floor space and consume about 93 kBtu/ft2·yr of site energy and 177.8 kBtu/ft2·yr of primary energy on average. Office buildings represent nearly one-fifth of all the delivered energy consumed by commercial buildings, and are therefore an important focus for energy efficiency improvements (EIA 2005) (Leach et al. 2010). Also as per 2009 building energy data book medical facilities comprise of roughly 2 billion square foot of floor space and consume almost 0.5 quadrillion BTUs.

The design of a building cooling system is influenced by multiple factors. (Pacific gas and electric company, 2007) Built-up cooling systems are complex assemblies whose performance (efficiency) and energy consumption depends on a wide range of players and parameters. Recently, the consuming public and other representative groups of building professionals have discovered the societal need to provide buildings that are more energy resource effective and environmentally compatible. (Grumman, 2003) Consequently evaluating and improving the system performance has become a major focus of researchers and engineers.

In practical applications of building simulation, explicit appraisal of uncertainty is the exception rather than the rule and most decisions are based on single-valued estimates (Malkawi and Augenbroe, 2003). Explicit expressions of uncertainty have not yet found its proper weight in system efficiency calculations in professional practice. The information about the building envelope, schedules and HVAC (Heating, Ventilating and Air Conditioning) components is not precise and their subjective choices can lead to large uncertainty in the results when using them as inputs in our simulation tools (Petr et al. 2007). Experience also shows (Cohen et al. 2001; Ruyssevelt et al. 1995) that there is a major credibility gap between design intent, the potential performance of the building as initially constructed, and the reality of everyday practical operation. (ASHRAE, 2010) Uncertainty enters the cooling system energy consumption and efficiency (ECaE) calculations from different sources, such as uncertainty in published equipment nameplate data, uncertainty in sensors accuracy, uncertainty in load profile (if assumed as a "design input", uncertainty in building material characteristics, etc. Each of these uncertainties causes the system to operate differently from the design idealization, and for that reason affects the ECaE of the system. This decreases the accuracy of the outcomes of energy simulations that is commonly used to quantify ECaE. In this thesis the quantification of the effects of uncertainty in equipment published nameplate data and cooling load profile on the overall ECaE of common cooling systems is the main goal. This accomplished by an uncertainty-based (probabilistic) methodology for calculating the chances (or risk) that a specific system could perform below a certain minimally acceptable efficiency level, and introducing them as appropriate "risk measure for helping practitioners and also energy performance contractors to select, design and guarantee systems that have a proven risk to underperform that is lower than what is deemed acceptable in a certain case.

ASHRAE 2008 provides detailed definitions of a wide verity of HVAC systems, ASHRAE 2010b suggests an acceptable measure of efficiency for different individual equipment and also lays out the structure for performing a building simulation for calculating the overall building ECaE with emphasis on HVAC system performance.

Due to the recent attention to conserving energy resources and environment conscious designs, engineers and energy performance contractors have been working hard to increase the efficiency of their buildings and HVAC systems along with improving the other building systems and material performance. As it is depicted in LEED 2009 and ASHRAE 2010b, the current accepted method for designing high efficiency buildings and systems is heavily reliant on simulation software packages to perform energy analyses of the intended building design and comparing the output against the results of a simulation of a baseline building design. Basically the current method of energy efficiency estimation is to show that the designed building has an energy consumption that is lower by a targeted improvement over the baseline model. Initially designers and contractors use simulation software to predict some level of improvement above the baseline energy consumption. This is to prove energy performance and (if desired by the client) to determine the LEED score in the AE category to achieve some level of LEED or similar standards certification. Later on they will be held responsible for the promised energy performances given at the initial stage of the design based on their limited information. These promises may or may not be realized when the building is in actual operation. It is customary that Energy Service Companies (ESCo) guarantee the performance of the building for as many as 10 to 15 years (Bleyl et al, 2009)(Bleyl et Schinnerl, 2008). These guarantees increase the risk of breaching contracts and expose design teams to possible lawsuits. As an actual example, a condominium developer in Maryland sued the contractor after the building failed to achieve a LEED Silver rating. As a result, the developer became ineligible for a $635,000 tax credit and sued the contractor for this amount. (Woolford, 2011) Also in a recent lawsuit, a school district sued the design team when green upgrades on three projects did not reduce operating costs by fifty percent. (Woolford, 2011)

Uncertainty and sensitivity analysis (UA and SA) are not new subjects in the building simulation research. On 1999 Macdonald assessed a risk in setup of building model in simulation tools and Lomas and Eppel (1992), De Wit ( 2001), Lam Hui, and others realized UA and SA in building performance simulation (Petr et al, 2007). Current commercial simulation software packages are, outside of some research applications, not directly capable of incorporating the effects of uncertainty in general and equipment performance uncertainty specifically into the energy model and therefore the simulation results from this point of view is not as informative as they should be.

A commercial simulation software package generally uses the published data of the performance of each system element at its full and part load condition to use at each time interval (hour) to calculate the cooling/heating system performance at the given time interval under that full or part load conditions. For this purpose simulation software packages use performance curves that are provided by the equipment test agencies. These performance curves represent the rate of change in the power input into the equipment as the rate of the delivered load (flow, capacity, etc...) of that equipment.

Air Conditioning and Refrigerant Institute (ARI) publishes standards in which it suggests acceptable performance ratings for most of HVAC equipment, such as chillers, air handling units, fans, heat pump and etc. Institutes such as Cooling Technology Institute (CTI) and Hydraulic Institute (HI) also publish guidance for acceptable performance rating of other equipment such as cooling tower, pump, etc. Methods, procedures and tolerances for testing the equipments are described in these standards, to be complied with by the equipment manufacturers in order to validate the manufacturer's published data. This data then is used for manufacturer's marketing purposes and of course as one of the requirements for selling their equipment. One of the essential parameters that allow the equipment manufacturer to be able to publish the equipment data under standard agency approval, is complying with the acceptable test tolerance for each equipment. Test tolerance is the maximum acceptable deviation from the testing agency's published data when the equipment undergoes a test procedure under the specified conditions. For example if the testing agency (e.g. ARI) specifies that a fan can consume 10 hp (horse power) to deliver 5000 cfm (cubic feet per minute) flow and can consume 5 hp to deliver 2500 cfm flow under certain pressure resistance and the test tolerance for the fan is equal to 5% under standard conditions, it means that if during the test, the fan consumes up to 10.5 hp to deliver 5000 cfm flow and up to 5.25 hp to deliver 2500 cfm flow under specified pressure resistances it is still approved for the specified rating by the standard agency. Therefore the manufacturer can present, tag and sell the equipment as a unit that consumes 10 hp power to deliver 5000 cfm flow, and consumes 5 hp power to deliver

2500 cfm flow. But in actual fact, after the equipment was installed it could consume up to 10.5 or 5.25 hp instead of 10 and 5 hp. This tolerance in actual performance then becomes a source of uncertainty, and we will try to evaluate the compound uncertainty of all components on overall system cooling consumption and efficiency in this research.

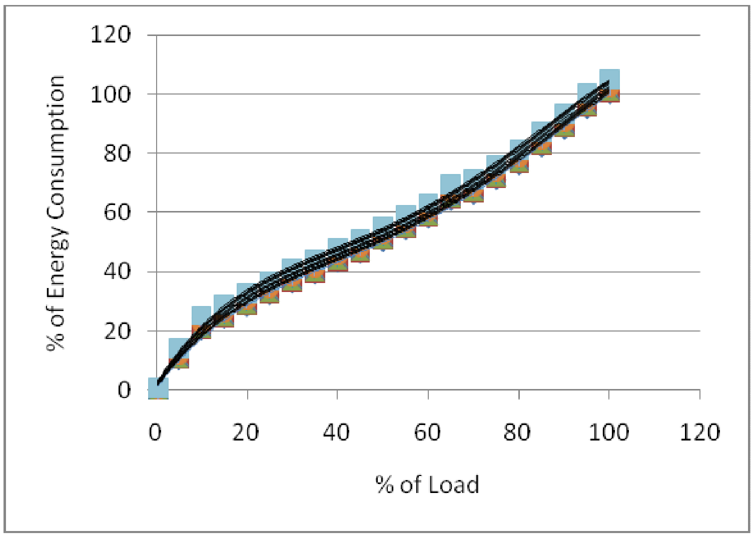


Figure 1.1: Typical chiller performance curve and allowable tolerance curves

Since each system consists of a number of composing elements (equipment components) and each one of these elements carries its specific nameplate tolerance, different systems configurations and even different installed equipment can result in different levels of ECaE while operating.

In the current engineering environment, practicing engineers and also energy contractors largely ignore the influence of equipment performance tolerance uncertainty on their system design, system selection, and system consumption guarantee. Therefore there is room for improvement by qualifying the reliability of the prediction of the overall system consumption and efficiency calculations.

In this research we will also investigate the reliability of the overall cooling system performance as it is being calculated in the current professional environment by attempting to quantify the effects of the equipment nameplate tolerance on the overall system ECaE in the presence of an uncertain load profile.

In order to use the equipment nameplate tolerance two assumptions were made. One assumption has been made in order to justify the use of the single curve presented by the testing agencies as the base for the energy modeling. Based on this, the performance of the equipment will not change under different outdoor conditions, as far as these conditions affect HVAC operation. This assumption means that equipment uses the same amount of electricity to create X amount of capacity despite changes in outdoor conditions. In fact the performance curve will change depending on weather, but the change is so insignificant that the same original curve could be used.

Another assumption that is fundamental for our approach concerns the fact that every component, will stay on a curve that is located between the minimum and maximum curves. This implies that we assume that the component performs perfectly according to a performance curve when that component leaves the factory. In practice this implies that the performance for the part load conditions stay on one curve similar but adjusted proportionally to the basic curve. The only source of uncertainty is that we don’t know which curve within the allowed range of tolerance curve applies.

In the next step, we will perform an uncertainty-base (probability) analysis on specific selected systems to calculate their overall ECaE based on the effects of the above mentioned uncertain parameter (in this case curve). Then we will compare these results with the results of a routine simulation of the same system overall efficiency when these factors are ignored (deterministic calculations). This comparison will help us to quantify the uncertainty in selected systems ECaE versus standard prediction.

In order to calculate the effects of uncertainty in equipment performance on the targeted systems overall ECaE, we will use two cases: simple office building and also a simple healthcare facility.

### 1.1. Approach:

Our approach in this thesis is as follows: First we create an excel-based normative model of the overall ECaE of a typical cooling system. The first model applies to a water-cooled chilled water system with variable air volume air handling system for a small to mid-size size office building (150 tons of cooling capacity). This model is modified to be able to calculate five other different systems. This model is able to calculate the overall ECaE of the selected system(s) based on the input variables from the demand side. As a minimum, the required inputs from the demand side to this model will be hourly room demand profile (sensible and latent loads), outdoor air flow, outdoor air condition, and their related uncertainties (for the probabilistic calculations). This model is capable of calculating both deterministic and probabilistic energy consumption of the system(s). The deterministic part of the model uses the deterministic cooling load profile, and the probabilistic part uses a probabilistic load profile. A degree of uncertainty (range of possible uncertainties) is assigned to a calculated deterministic load profile and uses the results as primary input to a probabilistic calculation. Therefore before being able to move to the building cooling system side, we need to gather this cooling load demand profile information. For a typical 150 ton office building the associated cooling load for a typical day in July for Atlanta, Ga. is generated. We use this profile for the deterministic calculations and also use the same profile as the base to add a range of possible uncertainties ( +_8 %) that then drive the probabilistic calculations.

A group of researchers (Dominguez-Munoz et al. 2010) performed a thorough analysis on the effects of multiple (more than 25) demand side components on the overall cooling system. Based on results of this research, cooling load uncertainty was shown to be in a margin of about (+-15%), but the possibility of the occurrences of the load below 4% and above 96% were extremely small and almost negligible. As a result the uncertainty in the cooling load in this thesis was originally selected to be in the range of (+_8%) of the base load. Only if it is found that the effect on the resulting energy consumption is significant a further inspection of this variability and its effect will be conducted. It should also be noted that the outcomes of this thesis will be used in the broader context of whole building, uncertainty analysis, where the uncertainty in the load is generated by a whole house simulation rather than assumed. This will be discussed in chapter 8.

On system side, after we specify the needed system and sizing parameters (e.g. total cooling capacity, total air flow, etc...) for each one of the constructing equipments, we use the testing agency's performance curves to calculate the required power at each instant for each of the system equipments. These curves need to be adjusted for the performance tolerances and therefore a family of curves is used to represent the tolerance span of the equipment performance. By doing this, we draw multiple curves close and basically similar to the basic equipment published curves, but within the test tolerance margin (see Figure 1). These curves are drawn with (intervals of one or half percent) from each other up to the limits of the maximum allowable underperformance tolerance of the equipment. Each curve relates the cooling demand load (flow, capacity, etc...) to the required power input to the equipment. The Model-Center software package is used to perform the actual simulation based on a traditional Monte-Carlo approach. The span of the calculation is one design day per month. In this study only one design day, for the month of July is used. The sampling and propagation produces the probability distribution of the results for ECaE of all the equipment based on an hourly basis and also as the full design. These results probability distribution is compared against the deterministically calculated ECaE of the system. The comparison leads to measures of reliability of the traditional energy efficiency calculations, and a testimony to the need (or lack of it) for uncertainty analysis in current professional design procedure. Of course other parameters such as sensor accuracy, duct leakage, and duct heat loss also contribute to the overall energy efficiency of the system; in future steps they could be easily included in the mathematical model for the overall energy efficiency of the system. Also lack of operation of the system under the standard condition and efficiency loss at the interface between different equipment can add to unexplained efficiency losses, but our main target in this thesis is to evaluate the effects of equipment performance tolerances on the overall system energy consumption. Other causes of uncertainty will be added in follow-up work. To compare across different systems the same analysis is conducted for several commonly used cooling systems. A comparison between these different systems could inform practitioners to change their selection criteria for finding the best system for given building applications.

Our work also targets sensitivity analysis of different systems, based on finding the most sensitive input parameter so that in optimizing the systems, these parameters receive special attention. Therefore at first it is necessary to perform the sensitivity analysis and find out the “strongest” input parameters which most affecting the results under observation. (Saltelli et al, 2008)

We therefore perform a sensitivity analysis on each system in order to find the most influential parameters on ECaE of it, which will provide a guide for the design practitioners, contractors and energy performance contractors to primarily target improvement on these parameters, for better results when they design, purchase or guaranty the performance of a facility.

## 1.2. Who can benefit from this thesis?

There is a large group of individuals, firms and agencies that can benefit in different ways from the results of this research:

* Engineers that select and design cooling systems can improve their decision making by selecting systems that not only consume less energy and have a higher energy efficiency level, but also have lower potential risk of energy underperformance.

* Energy performance contract firms that guarantee the amount of consumed energy of a facility for a long period of time can use the presented method here to gain a better

understanding of the potential cooling system underperformance and include uncertainty calculations in their upfront estimate of the facility energy consumption.

* Energy codes and standards contributors and energy analysts can use the presented method for adding to, and improving their performed simulation outcome, by including algorithms that can include the effects of uncertainty in their calculations, and thereby reveal uncertainty in the simulation results and as a redefine future compliance as “showing with a certain degree of confidence that the building passes a mandated efficiency threshold”.

* Commissioning agents can use the presented method to recognize if the underperformance falls in the range of what could be expected, given the existence of unavoidable tolerances in component performance.

* Owners will benefit from it by attaining knowledge that gives them a more realistic potential energy cost for their buildings as well. This will help them to avoid confronting unexpected costs.

## 1.3. Hypothesis

This thesis is driven by two major hypotheses, and two sub-hypotheses:

1. It is hypothesized that use of uncertainty analysis can improve the knowledge of all the involved parties in the design process of the built environment about probable system energy consumption and achievable system efficiency levels, therefore improving their decision making and decreasing the risk of overstating the system efficiency and understating system energy consumption.

• Sub-Hypothesis 1: Current simulation based system efficiency calculation methods are inadequate since they do not relate cooling system ECaE rates to equipment nameplate tolerances, and cooling load profile uncertainty.

• Sub-Hypothesis 2: A new integrated design procedure can be developed that enables the system design engineers and contractors to calculate and compare cooling system consumption and efficiency in the light of quantifiable uncertainties in the system components.

2. It is hypothesized that uncertainty/ sensitivity analysis can specify the most important factors contributing to the variability of system ECaE and therefore can be used as a tool for improving system selection, system design and also maintaining the system efficiency.

### 1.4. Goals of this research

LEED 2009 targets levels of energy performance above a baseline model as calculated in compliance with section 11 or Appendix G of ASHRAE 2010b. The comparison is between an imaginary baseline building designed with all the listed energy saving requirement in ASHRAE 2010b and the real proposed design building. The target is to show how much better the real building can perform compared to the imaginary baseline building. Neither LEED 2009 nor ASHRAE 2010b pays any attention to the impact of uncertainty on the performance of the real building. Many sources of uncertainty need to be considered, both on the building (demand) side as well as on the HVAC system (supply) side. The outcome of this thesis which focuses exclusively on the HVAC system side, will help (1) selecting systems with higher probability of consuming less energy, when considering the effects of equipment performance tolerances and uncertainty in cooling load profile; (2) choosing which one of the parameters is the most influential in system overall energy performance; (3) calculating the probability of a typical cooling system energy performance not to be worse than a specific targeted value; (4) underscoring the urgent need for improving commercial energy standards in a way to be capable of including the effects and language of uncertainty in their proposed energy modeling methods.

The main goal of this thesis is to question the validity of the current industry environment that is enforcing the system design engineers and building contractors to quantify and guarantee the energy performance of the designed buildings through commercial energy standards by using simulation methods. The intent is to show that even though currently the design engineers and contractors are offering such quantifications and guarantees in order to score points in programs such as LEED, from a realistic point of view the actual energy performance of the building can be neither quantified nor guaranteed unless uncertainty and risk analysis becomes an inseparable part of the building energy analysis, and the building energy performance can be demonstrated by uncertainty parameters and arguments.

Therefore the ultimate goals of this research are to investigate the feasibility of:

(1) improving decision making that leads to effective building cooling system selections;

(2) avoiding guaranteeing/promising unachievable cooling system efficiency levels, by including system uncertainty analysis at design or energy contracting stage;

(3) estimating the potential causes of commercial cooling system ECaE inaccuracy;

(4) establishing a systematic approach for developing expressions of risk in commercial cooling system ECaE calculations, early in system selection and design;

(5) using expressions of risk as design targets and thus ensure system performance at a level that the various stakeholders will gain confidence in cooling system ECaE.

### 1.5. Research contribution and methodology

The main contribution of this thesis is making a contribution to improving the decision making process in all aspects of the design-built environment by providing directions for establishing risk indicators that can be used by all the involved parties. These indicators can help them to understand the amount of risk that they are undertaking while performing their design-built role. The other contribution of this research is that by performing the planned steps in this research we will show the overall cooling system ECaE as it is calculated by current deterministic simulation method can have a considerable deviation from the overall cooling system ECaE when the uncertainty of some parameters are included in the energy performance modeling. This validates the requirement of including uncertainty analysis in overall cooling ECaE calculations.

The planned methodology in this thesis consists of the following steps:

1. Conducting a literature review to analyze the current state in commercial cooling system performance indicators, design guidelines, rating systems, and usage of uncertainty analysis as part of current procedure

2. Interviewing leading HVAC system designers to get an idea of the current shortages, needs and wishes of design practice.

3. Developing an Excel-base model capable of calculating hourly cooling system ECaE based on testing agency's equipment performance data (curves) and design day related cooling load profile deterministically. In this model we divide the cooling systems that are studied, into its mechanical equipments. All systems are studied for the maximum cooling load design day in July, and calculations are performed hourly. The calculations generate hourly energy consumption (KW) and energy efficiency (KW/Ton) for each cooling component based on their individual performance curves. Summation of all these component energy consumption and averaging the efficiencies represents the overall ECaE of the cooling system.

4. Using this model in conjunction with Model Center software to calculate the effects of the equipment performance tolerances and the uncertainty associated with the cooling load profile.

As explained earlier, the uncertainty in the performance of each component is represented by a set of performance curves that span the variability between the equipment nameplate performance curve (zero tolerance) towards the maximum allowable equipment performance tolerance set by the test standard agencies (e.g. ARI, CTI, etc.). Each purchased equipment, is assumed to perform along one of these tolerance related performance curves. The set of curves is generated with an increment of 0.5% deviation, starting from 0% (nameplate) towards the maximum of either 5 or 7.5% maximum deviation from the nameplate performance as allowed by the testing standard. The deviation is parameterized by a discrete parameter PerfDev over the domain (0, 0.5, 1.0, 1.5, etc…-max), where max is 5 or 7.5. A probability distribution of PerfDev over this interval has to be chosen, as will be discussed in the next chapter. This is done for each component and an additional parameter is added to parameterize the load uncertainty. Degradation over time can be easily incorporated by adding an additional parameter to each component which represents the rate if yearly degradation, which can be applied as a multiplier for each performance curve.

The Model Center software is used to perform a Monte Carlo simulation for each system sampling from the parameter distributions introduced above. At the end of the simulations, probability distributions of the hourly ECaE of individual equipment and for the overall cooling system are calculated. These results can be compared with the results of the traditional deterministic ECaE of the same cooling system.

5. Comparison and analysis of the results of deterministic and probabilistic approaches to arrive at indicators to enable:

a) design practitioners in the early design stage to select a cooling system for their application that has the highest chance of consuming the lowest quantity of energy;

b) energy performance contractors to reduce the risks associated with their long term facility energy cost guaranties.

c) building owners to have a more realistic understanding of the possible cooling system consumption, efficiency and operational cost of their buildings, after equipment is installed.

d) design practitioners, building contractors, and owners to have a better understanding of the effects and degree of importance of different equipment performance tolerance, so they can demand higher performance standards from the testing agencies and manufacturers, and allocate resources for purchasing the equipment with the highest possible payback (lowest tolerance from the nameplate information).

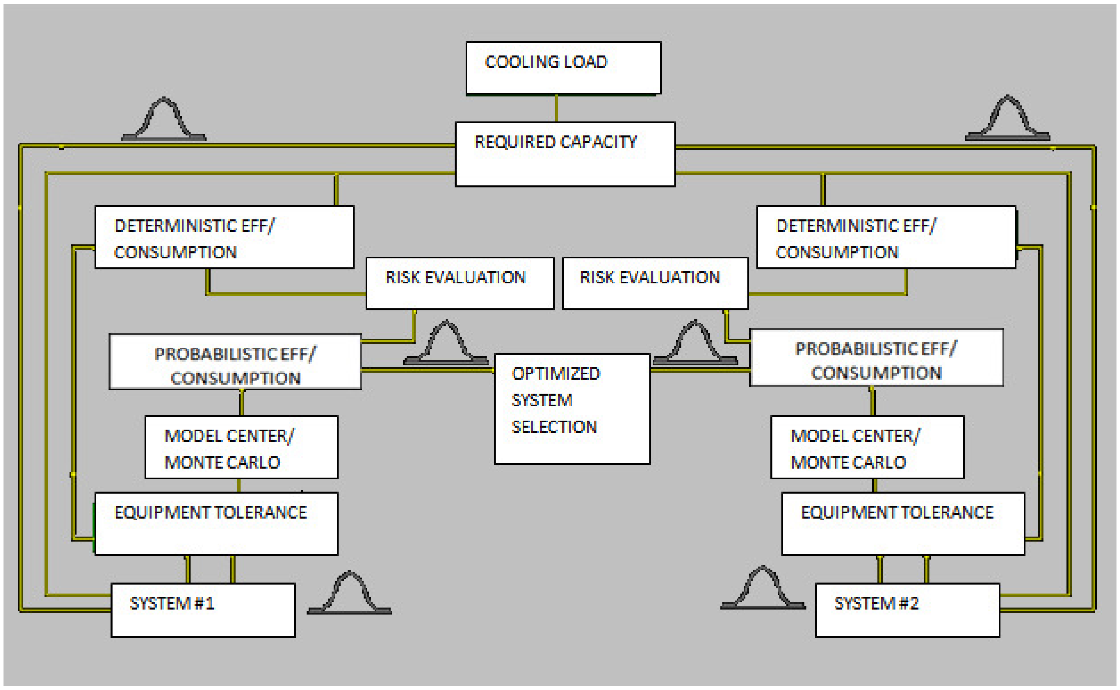


Figure 1.2: Planned Methodology for system selection and system risk analysis

6. Tabulation of the results of the sensitivity analysis for each system, to provide proper ground for the design practitioners and contractors to know the most influential parameters on the overall system ECaE, and therefore to target these parameters first and most to improve the efficiency of their systems.

7. Reducing the tolerances in these will show the level of consumption saving that would arise from the system if we can get the manufacturers to build and guaranty the equipment with smaller tolerances.

8. Providing a methodology that uses the above analysis outcomes in a way that design practitioners and energy contractors would be able to predict the chances of the system to perform above/ under a certain level. This will be key data specifically for the energy

contractors, since they can include this method in their calculations before signing their guarantee contracts.

It should be pointed out that all of the above steps will confined to the HVAC systems, where the building load uncertainty has been assumed in a certain range (as discussed in next chapter). In ongoing research, an uncertainty analysis of the building as a whole will be integrated with the system uncertainty analysis developed in this thesis. At that stage many of the objectives started above will be met at the whole building level. As this thesis only treats the system uncertainties, it is primarily significant for the current HVAC discipline which regards the building load as an input. The farther reaching goal is that system uncertainty analysis will be fully integrated in building simulation under uncertainty. This thesis delivers a building block towards that goal.

### 1.6. Objectives of the thesis

By using the proposed approach, we will (1) better understand the performance risk involved in design and operation of commercial buildings in regards to its component tolerances, (2) change the outcomes of building and systems design by using risk expressions as part of the design targets, (3) arrive at overall energy savings in the amount of up to X% by introducing a new risk based method for proper system selection, (4) avoid guaranteeing unachievable levels of efficiency by encouraging the incorporation of risk language into current ruling energy efficiency standards, (5) encouraging the testing agencies to set down a more restricted standard for acceptable tolerances of individual equipment power consumption and (6) introduce a new system indicator (e.g. based on “percentage better than average; BTA. This indicator is easily understandable for all the parties in design built environment, and will show the percentage energy savings of one system compared to the average energy consumption of suitable systems for that application.

# CHAPTER 2

# LITERATURE REVIEW

## 2.1. History

Wind towers were used to provide natural air conditioning and humidification in hot and dry climates as early as fourth millennium B.C. in central parts of Iran. These towers consisted of a few major parts. The body and shelves which prevented the hot air from entering the structure, flaps which redirect wind circulation near the top of the structure, and a roof. Wind moved through the structure from the top of the tower and reached the interior of the building. The air flow inside the structure traveled in two opposite directions, up and down. The temperature difference between the interior and exterior of the building was the source of pressure variations which resulted in the generation of air currents. A cistern in the bottom of the tower used to help controlling the humidity of the interior of the structure when air moved over it.

Samuel Sugarman in his book “HVAC Fundamentals” that was published in 2007 has a comprehensive look at HVAC systems history and operations. In this book he divides the timeline of HVAC systems into four major eras. Based on his research, in the period between years 1000 and 1500, a series of important inventions that were related to HVAC systems development, started by utilizing man powered fans by Egyptians, and ended by invention of water driven fans designed by Leonardo Da Vinci. Between 1500 and 1700, the people of France used machines for ventilation of mines, while Galileo invented the thermometer and Ferdinand II developed a thermometer independent of air pressure. Between 1700 and 1900 Fahrenheit invented the mercury thermometer, Benjamin Franklin invented the first steam heating system followed by James Watt's steam engine, Carnot founded thermodynamics and James Joule discovered that work produces heat, and heat started to be considered as energy. In this era the law of conservation of energy was discovered, along with first and second law of thermodynamics. After 1900 HVAC systems improved dramatically and systems such as the furnace with centrifugal fans, and high pressure steam heating systems were widely used. The first centrifugal refrigeration machine was made for air conditioning of large spaces. Pumps and radiators started to be used and the first refrigeration with a compressor was invented which led to residential air conditioning systems.

## 2.2. Recent Events

Extreme usage of refrigerants in cooling machines endangered the atmosphere by depleting ozone, and uncontrolled consumption of energy sources jeopardized the energy resources. Therefore different protocols and committees started to look for higher efficiency systems with lower damage to the environment and use of sustainable energy sources. One of the most internationally influential organizations in this field is ASHRAE (American Society of Heating, Refrigerating and Air Conditioning Engineers which was founded in 1894 at a meeting of engineers in New York City. ASHRAE publishes a monthly magazine, a yearly handbook, and performs multiple meeting. Its four handbooks of Refrigeration, Fundamentals, HVAC Systems and Equipment and HVAC Applications that is revised and re-published every four years are one of the most valuable resources for designers and researchers in HVAC field. ASHRAE also has published numerous standards regarding most aspects of design, control and commissioning of HVAC systems. The instructions of ASHRAE Standard 90.1 (ASHRAE 2010b), otherwise known as Energy Code are basically what all the designers shall follow to be able obtain a building energy compliance permit throughout the United States. LEED (Leadership in Energy and Environmental design), established in 1993, is an internationally recognized green building certification system that verifies that a building is designed and built using strategies aimed at improving performance across all the important metrics such as energy saving and $CO_2$ emission. From 1994 to 2009, LEED grew from one standard for new construction to a comprehensive system of six standards covering all aspects of the development and construction process.

In 2009 in order to create a labeling system for the different buildings ASHRAE started working on a labeling program to be fully lunched in 2011. The target of this program is to provide the building community with information on the potential and actual (measured) energy use of buildings. This information is useful for a variety of reasons such as, to verify how a targeted building compares to peer group buildings, to measured it against the highest performing buildings, to estimate potential for energy performance improvement, to reveal to potential buyers or tenants the long-term cost of a building, and to use market-based forces to influence energy efficiency investment opportunities. The ASHRAE Advanced Building Energy Labeling (ABEL) program is based on the Building Energy Quotient (bEQ) label, together with a supporting certificate. The label is applicable to existing buildings, using the as operated (operational) rating, and to new buildings using the as designed (asset) rating. The ratings are designed to support regulatory energy use disclosure requirements, and are supported by a user instruction manual and forms for use and development during the prototype phase of the program. (ASHRAE 2009)

In 2009 ASHRAE, LEED and ANSI (American National Standard Institute) and IES (Illuminating Engineering Society) put their forces together and published a comprehensive standard 189.9-2009, "Standard for the Design of High-Performance Green Buildings-Except Low-Rise Residential Buildings". The purpose of this standard is to provide minimum requirements for the site selection, design, construction, and plan for operation of high-performance green buildings to balance environmental responsibility, resource efficiency, occupant comfort and well being, and community sensitivity, and also support the goal of development that meets the needs of the present without compromising the ability of future generations to meet their own needs.
CEN (European Committee for Standardization) which is a non-profit organization and its mission is to foster the European economy in global trading, the welfare of the European citizens and the environment by providing an efficient infrastructure to interested parties for the development, maintenance and distribution of coherent sets of standards and specifications, was established in 1961. One of the goals of CEN is to provide a unified standard for energy conscious design throughout Europe.

Other similar committees and efforts for standardization of the energy conscious design have been working towards sustainable and energy efficient buildings in Canada, U.K., Japan and Qatar.

To comply with ASHRAE standard 90.1 among other sections, section 6 “Heating, Ventilating, and air Conditioning” requirements, and section 6.8 “Minimum Equipment Efficiency” describe the minimum acceptable efficiency for all the equipment. This information is provided in the form of multiple tables which specify the equipment type, capacity and minimum acceptable performance of the equipments. The test procedure for recording this information is also given. Depending on the type of the equipment these performance scales could be COP (Coefficient of Performance), EER (Energy Efficiency Ratio), or IPLV (Integrated Part Load Value). In section 6.5 “Prescriptive section” ASHRAE standard 90.1, sets the rules for allowable nameplate motor power for fan systems based on hp/1000 cfm (horse power/ 1000 Cubic Feet per Minute) measure. A similar approach has been chosen by the CEN standard regarding the HVAC equipment efficiency.

All these efforts show that building design and operation in general and HVAC system design and operation as one of the important energy consumers in the building is increasingly focusing on energy efficient design. For example, out of 100 points available for LEED 2009 certification for new constructions, in EA (Energy and Environment) section, 19 points are designated for optimizing energy performance and 3 points are designated for measuring and verifying the system components, and additional credits are awarded in the IEQ (Indoor Air Quality) section are designated for controlling and monitoring preferable condition for indoor air quality. These points are directly related to the HVAC system efficiency and operation e.g. outdoor air delivery monitoring and thermal comfort controllability.

The design engineer is responsible for considering various systems and recommending one or two systems that will meet the project goals and perform as desired (ASHRAE 2009). In other words, in the current environment the most desired quality of any HVAC system is to perform efficiently, with minimum energy consumption.

### 2.2.1. Overall system efficiency versus equipment efficiency

Professor Steve Kavanaugh and his students in University of Alabama, in an attempt to replace the equipment efficiency with system efficiency, have provided a tool to calculate the efficiency of a few typical HVAC systems, given the efficiency of their individual equipment. This tool “HVACPowDen08.xlc” can be found at “http://www.geokiss.com/hsoftware.htm”. It sums the power requirement of all system components (Chiller, Cooling Tower, Fan, Terminal Units and Pumps), deducting cooling capacity for heat input of interior auxiliary equipment and then compute the net system efficiency using three common units of measure KW/Ton, EER and COP. This tool like other existing methods is a static measure that relies on the single equipment efficiencies at full load condition, and does not account for the effects of uncertainty.

### 2.2.2. Status of the current simulation software

There is plenty of available simulation software packages in the current market. The U.S. Department of Energy (USDOE) provides a complete list and (Crawley et al. 2005) makes a thorough comparison among the most used building energy performance programs. A review of characteristics, inputs and outputs of the most common programs can be found there.

# CHAPTER 3

# UNCERTAINTY AND SENSITIVITY ANALYSIS

## 3.1. Uncertainty and Sensitivity definitions

"Decision theory is concerned with making rational choices between alternatives by applying (mathematical) methods. Within decision theory a distinction is made between single- and multiple attribute decision problems, depending on the number of descriptors (attributes) that are needed to specify the consequences of a decision. Also a distinction is made between problems under certainty or uncertainty. For problems under certainty the consequence(s) of a decision are known; for problems under uncertainty there is a range of possible consequences. Making decisions under uncertainty involve taking (or limiting) risks." (Wilde et al, 2001)

A possible definition of sensitivity analysis is the following: The study of how uncertainty in the output of a model (numerical or otherwise) can be apportioned to different sources of uncertainty in the model input (Saltelli et al., 2004). A related practice is "uncertainty analysis", which focuses rather on quantifying uncertainty in model output. Ideally, uncertainty and sensitivity analyses should be run in tandem, with uncertainty analysis preceding in current practice. (Saltelli et al., 2008)

An uncertainty analysis (UA) allows the modelers to study the changes in the output of their model when they change the inputs. The modeler gains multiple benefits from the uncertainty analysis. Uncertainty analysis helps the modeler to make better decisions by better understanding the system, and provides ground for discussion and communication among the people of interest in the model outcome.

Sensitivity analysis is a method that calculates the uncertain parameters which have the most influence on the outputs. There are many obvious benefits to this type of analysis because once the most influential parameters are identified, more engineering attention can be placed on them (e.g. for model calibration (see (O'Neill et al., 2011)), building or control design, and for online diagnostic algorithms). (Eisenhower, 2011)

Sensitivity analysis can serve a number of useful purposes in the economy of modeling. It can surprise the analyst, uncover technical errors in the model, identify critical regions in the space of the inputs, establish priorities for research, simplify models and defend against falsifications of the analysis. In the context of models used for policy assessment, sensitivity analysis can verify whether policy options can be distinguished from one another given the uncertainties in the system, and so on. (Saltelli et al, 2008)

## 3.2. Uncertainty types

In most of the literature uncertainty has been defined to be of either Aleatory (based on pure chance) or Epistemic (knowledge based) type.

When we are working with complex systems, the uncertainty and sensitivity analyses can play a significant importance. Uncertainty analysis is basically the evaluation of the changes in the outcome of the function as a result of changes in the functions inputs, while sensitivity analysis is the determination of the contribution of changes of an individual input on the functions output. Helton in his work (Helton et al. 2006) describes that, the uncertainty under consideration in a model is often referred to as epistemic uncertainty; and alternative designations for this form of uncertainty include state of knowledge, subjective, reducible, and type B. He also states that epistemic uncertainty derives from a lack of knowledge about the suitable value to use for a quantity that is assumed to have a fixed value in the context of a particular analysis. Finally he argues that in the conceptual and computational organization of an analysis, epistemic uncertainty is generally considered to be distinct from aleatory uncertainty, which arises from an inherent randomness in the behavior of the system under study. An alternative designations for the second type of uncertainty include variability, stochastic, irreducible, and type A.

In this research all the uncertainties that we are working with are from the epistemic category. Epistemic type uncertainty is usually divided into three or four major types of physical, design and scenario. In some literature numerical error are counted as fourth type of epistemic uncertainty. In the field of building simulation physical uncertainty is usually referred to as the lack of knowledge about the physical characteristics of the material which the designer does not have any influence on controlling it. For example this type uncertainty appears in slightly different heating characteristic of the building material, in a group of the similar material or even in any individual element part of a group.

A design uncertainty derives from either lack of knowledge of the designer or is related to the different systems that designer uses. (Numerical mistakes can be either categorized separately under numerical errors or in this category "design uncertainty", depending on if either three or four categories have been considered for the epistemic uncertainties.)

Scenario uncertainties are divided into internal and external categories. In building environment internal scenario covers related uncertainties to the internal use of the building such as number of people, and lighting schedules. External scenario is referred to the environment outside the building such as weather condition, and is mostly considered as given as a fixed scenario (captured typically as a standard weather file for a given location).

## 3.3. Uncertainty quantification techniques

Basically there are two main approaches - external and internal - for quantification of uncertainty. Both are based on statistical techniques.

### 3.3.1. External Methods

The essence of external methods is that the mathematics of the simulation are not altered, only the describing model, initial conditions, boundary conditions and solution methods. This results in the simulation software being treated as a black box, where different models are analyzed and the differences in response examined. (McDonald, 2002)

This method basically evaluates the effects of uncertainty from the outside of the system. For example in an external method, in a computer simulation model, the simulator changes the input parameters and his goal is to implement and then evaluate the effects of these changes on the model output.

There are two main categories - local and global - in external methods. A local method shows the effect of change of an individual parameter on the uncertainty of the output of the model, while a global method shows the effects of change of multiple parameters on the uncertainty of the model.

As it is explained in depth in (Hoes and de Vann, 2005) the comparison between local and global methods are as follows: (1) The aim of local methods is to determine the partial derivation of the output in relation to input, but in global methods the aim is to determine the uncertainty of a specific input parameter in relation to the overall outputs; (2) Input parameters in local methods are sampled one by one, but in global methods input parameters are sampled simultaneously; (3) The correlation between input and output of the local and global methods both are assumed to be linear; (4) In local methods there is only one distribution assigned to input, but in global methods different distribution for each input parameter is possible; (5) In local methods the distribution is based on assumed boundaries that are usually valid for all variables, but in global methods the distribution of input is based on an assumed distribution of each parameter which implies an insight in the behavior of the parameters.

#### 3.3.1.1. Local Methods

Local methods can be only applied if the correlation between inputs and outputs is linear. (Hopfe, 2009). There are two types of local methods, differential sensitivity and factorial method.

Helton et al. (2006) explains in differential sensitivity analysis method the effects of change of an individual input parameter on the uncertainty of the output is evaluated. Each set of simulation will be made of three simulations (one original simulation and two other simulations at the upper and lower limits of the input parameter (e.g. +3σ and -3σ), and the results from these three simulations will be analyzed to give a better understanding of the effects of the individual parameter changes on the output of the simulations. This method is easy to perform and interpret results, but the weakness of the method is that each input is assumed to be independent from all the others.

In the factorial method, during all the simulations all the uncertain parameters alter between either (+3σ and -3σ) for a total of $2^N$ (N is number of uncertain parameters) or between (+3σ, mean and -3σ) for a total of $3^N$ iterations. It is claimed that this method is more suitable for identification of the most influential parameter, than quantification of the output uncertainty. Cotter's and Morris's methods are similar and revised versions of factorial method.

Mc Donald in his work (McDonald, 2002) states that the differential and factorial methods are deemed suitable for use in building simulation due to their robustness and ability to accurately quantify the uncertainty in the model output.

#### 3.3.1.2. Global Methods (Sampling based Methods)

In global methods the uncertainty in a specific input parameter is used to determine the uncertainty in the output. All variables are sampled simultaneously. (Hopfe, 2009) Helton et al. (2006) has presented a complete overview of sampling based methods. He states the analyses of this type, involves the generation and exploration of a mapping from uncertain analysis inputs to uncertain analysis results. In other word, the underlying idea is that analysis results $\mathbf{y}(\mathbf{x}) = [y_1(\mathbf{x}), y_2(\mathbf{x}), \ldots, y_{nY}(\mathbf{x})]$ are functions of uncertain analysis inputs $\mathbf{x} = [x_1, x_2, \ldots, x_{nX}]$, and in turn, uncertainty in $\mathbf{x}$ results in a corresponding uncertainty in $\mathbf{y}(\mathbf{x})$. He continues with presenting the following two questions: (i) What is the uncertainty in $\mathbf{y}(\mathbf{x})$ given the uncertainty in $\mathbf{x}$?, and (ii) How important are the individual elements of $\mathbf{x}$ with respect to the uncertainty in $\mathbf{y}(\mathbf{x})$? He answers his questions as the goal of uncertainty analysis is to answer the first question, and the goal of sensitivity analysis is to answer the second question.

Later Helton (Helton et al., 2006) continues and depicts the following five basic components that underlie the implementation of a sampling-based uncertainty and sensitivity analysis: (i) Definition of distributions $D_1, D_2, \ldots, D_{nX}$ that characterize the epistemic uncertainty in the elements $x_1, x_2, \ldots, x_{nX}$ of $\mathbf{x}$, (ii) Generation of a sample $\mathbf{x}_1, \mathbf{x}_2, \ldots, \mathbf{x}_{nS}$ from the $\mathbf{x}$'s in consistency with the distributions $D_1, D_2, \ldots, D_{nX}$, (iii) Propagation of the sample through the analysis to produce a mapping $[\mathbf{x}i, \mathbf{y}(\mathbf{x}i)]$, $i = 1, 2, \ldots, nS$, from analysis inputs to analysis results, (iv) Presentation of uncertainty analysis results (i.e., approximations to the distributions of the elements of $\mathbf{y}$ constructed from the corresponding elements of $\mathbf{y}(\mathbf{x}i)$, $i = 1, 2, \ldots, nS$) , and (v) Determination of sensitivity analysis results (i.e., exploration of the mapping $[\mathbf{x}i, \mathbf{y}(\mathbf{x}i)]$, $i = 1, 2, \ldots, nS$) .

Helton (Helton et al. 2006) emphasizes that in characterization of uncertainty, definition of the distributions $D_1, D_2, \ldots, D_{nX}$ that characterize the epistemic uncertainty in the elements $x_1, x_2, \ldots, x_{nX}$ of x is the most important part of a sampling- based uncertainty and sensitivity analysis as these distributions determine both the uncertainty in y and the sensitivity of the elements of y to the elements of x.

He recommends that the distributions $D_1, D_2, \ldots, D_{nX}$ should be typically defined through an expert review process, in which their development can constitute a major analysis cost. In order to prevent such costs, he recommends a strategy that includes of performing an initial exploratory analysis with rather crude definitions for $D_1, D_2, \ldots, D_{nX}$ and then using sensitivity analysis to identify the most important analysis inputs. After this all the resources can be focused on characterizing the uncertainty in these inputs and then a second presentation or decision-aiding analysis can be carried out with these improved uncertainty characterizations.

For the generation of samples there are different methods available, which among them the most popular sampling method strategies are random sampling, importance sampling, and Latin hypercube sampling. Among them the importance of the Latin hypercube sampling in complicated systems is its efficient stratification properties that help to use only a small number of sample sizes.

Helton (Helton et al. 2006) further explains that basically in Latin Hypercube sampling for X variables, the range of each variable shall be divided into Y equally probable segments. In this method the number of segments (Y) should be equal for all the variables, so each variable receives equal number of samples (Y). The maximum number of possible combinations in a Latin Hypercube will follow the following formula.

Number of possible combinations = $(Y!)^{X-1}$

Therefore a set of 3 segments with 4 variables will have 216 possible combinations.

Sampling-based approaches to uncertainty and sensitivity analysis have been shown to be effective and have been used frequently in different research work. In practice, the implementation of an uncertainty analysis and the implementation of a sensitivity analysis are very closely tied together (Helton et al. 2006). Among different sampling methods the one that have gotten the most use in research work has been the Monte Carlo method.

#### 3.3.1.2.1. Monte Carlo Methods

Main method of global category is Monte Carlo method and basically each time, all the uncertain parameters are perturbed by a random quantity before the next simulation is performed. In this method the number of simulation and number of uncertain input parameters are independent and an acceptable number of iteration as per (McDonald, 2002), is usually 80 iterations.

In Monte Carlo method a risk analysis by creating model of possible results based on substitution of the uncertain inputs from a range of values (probability distribution) is performed. Each time a different set of random values are pulled from the different distributions and is put into the model, and as a result each time a new outcome is calculated. This process continues (based on number of specified iterations) and finally a possible distribution for the outcome will be generated.

#### 3.3.1.2.2. Stratified Sampling

In this method members of the population are divided into homogeneous segments before sampling. Every sample shall be assigned to only one group, and all the groups together shall create a whole body of possible samples. Then random sampling applies within each segment.

#### 3.3.1.2.3. Random Sampling

In this method samples are gathered from a random pool such as random numbers from a database and will be scattered without any limiting rules across the sampling field. This method can create clusters (when samples are very close to each other) or gaps (when very little number of samples are taken from some regions).

The first step in this type of sampling is propagation of sample to create mapping between inputs and outputs, which is often the most computationally demanding part of a sampling-based uncertainty and sensitivity analysis. The details of this propagation depend on the specific required analysis that can be very simple or very complicated, based on simplicity or complexity of the used model(s).

When a single model is under consideration, this part of the analysis can involve little more than putting a DO loop around the model that (i) supplies the sampled input to the model, (ii) runs the model, and (iii) stores model results for later analysis. When more complex analyses with multiple models are involved, considerable sophistication may be required in this part of the analysis. Implementation of such analyses can involve (i) development of simplified models to approximate more complex models, (ii) clustering of results at model interfaces, (ii) reuse of model results through interpolation or linearity properties, and (iv) complex procedures for the storage and retrieval of analysis results. (Helton et al., 2006)

#### 3.3.1.2.4. Screening Methods

Screening methods are a particular case of sampling based methods. Like other sampling based methods (e.g., Monte Carlo) they also consider the global sensitivity meaning the input parameter are varied over the whole range of their possible values. (Hopfe, 2009) Screening method is another method that deals with each input individually. It is also known as once at a time (OAT) method. After all the desired inputs one by one changed the designer evaluates the results and makes decision based on the comparison between the outputs. Morris method is known as the most widely used screening method.

#### 3.3.1.2.5. Variance based Methods

Variance based methods are sampling-based methods but besides, they rely on the computation of conditional variances. They allow a global, quantitative and model independent sensitivity measure. Therefore, it is also understood as sort of subset of, e.g., Monte-Carlo based methods. (Hopfe, 2009)

Variance based methods are of great importance if the model contains unknown linearity or additivity (Saltelli et al., 2008).

This method is known to be more complex than the other methods.

### 3.3.2. Internal Methods

These methods deal with conditions that the uncertainty is considered in the arithmetical equations of the model. Since these methods are out of the scope of this thesis we only briefly introduce them here.

#### 3.3.2.1. Basic treatment

Treatment of error in a simple equations provides a value ($\alpha$) consists of its true value ($\bar{a}$) and the assigned error ($\varepsilon$). ($|\varepsilon|\leq\beta$)

#### 3.3.2.2. Error propagation

The error in addition and subtraction is less than or equal the sum of the original errors, but in multiplication and division operation an additional item (relative error) will be created and therefore the error is less than or equal to the sum of the original relative errors. This method ignores the relationship between the parameters and creates an overestimation by overestimating the maximum uncertainty.

#### 3.3.2.3. Range arithmetic overview

These methods are based on interval arithmetic which is a form of fuzzy arithmetic. In these methods the equations are being calculated where the parameters are represented by a range of numbers instead of an individual number.

#### 3.3.2.4. Interval arithmetic

In this method each interval is defined as a range in a set of the real numbers, and each value of the number has an equal chance inside the range. Computation of interval arithmetic is consists of methods such as binary function, unary functions, linear interval equations, direct solution and indirect solution. The main problem with this method is that it provides all the solutions and some additional non-solution results at the same time.

#### 3.3.2.5. Fuzzy arithmetic

The difference between interval arithmetic and fuzzy arithmetic is that in interval arithmetic chance of all the numbers in an interval is equal, but in fuzzy arithmetic the existence of the numbers are defined as a function that shows the ambiguity in the value of the number in an interval.

#### 3.3.2.6. Affine arithmetic

In this method in addition to the advantages of the interval arithmetic, tracking of the correlation between data is targeted.

### 3.3.3. Uncertainty results presentation

Presentation of uncertainty analysis results is generally straight forward and involves little more than displaying the results associated with the already calculated mapping [$\mathrm{x}i$, $\mathrm{y}(\mathrm{x}i)$], $i = 1, 2, \ldots, nS$. Presentation possibilities include means and standard deviations, density functions, cumulative distribution function (CDFs), complementary cumulative distribution functions (CCDFs), and box plots. (Helton et al., 2006)

Determination of sensitivity analysis results is usually more demanding than the presentation of uncertainty analysis results due to the need to actually explore the mapping [$x_i$, $y(x_i)$], $i = 1, 2, \ldots, nS$, to assess the effects of individual elements of x on the elements of y. (Helton et al., 2006)

The followings are a few approaches to sensitivity analysis presentations that usually can be seen as the representatives of the sensitivity analysis.

Scatter-plots: A plot of the points that can show the relationship between models inputs and outputs. Even if the system is complicated and requires more advance technique for sensitivity analysis, usually the scatter-plot technique is a very good starting point for understanding the relation between model inputs and outputs.

Correlation: Correlation depicts the degree of strength of the linear relationship between $x_j$ and y. Correlation Coefficient (CC) has a value between -1 and +1. Positive correlation between two factors means as one increases/decrease the other will increase/decrease as well, and a negative correlation between two factors means as one increases/decreases, the other will decrease/increase. Other known approaches are regression analysis, partial correlation, rank transformations, statistical tests for patterns based on gridding, entropy tests for patterns based on gridding, squared rank differences/ rank correlation coefficient, two dimensional Kolmogorov-Smirnov (KS) test, test for patterns based on distance measures, variance decomposition, and top down coefficient of concordance (TDCC).

### 3.3.4. Uncertainty in system Simulation

In experimental work measurements are made which are subject to error and in simulation work data supplied to the model is also likewise subject to error. (McDonald, 2002)

#### 3.3.4.1. Measurement theory

Measurement uncertainty is made of two parts of systematic and random errors. A systematic error is a result of the measurement process. A systematic error is usually either constant or changes regularly when the repeated measurements being done. A random error is not related to the measuring process and changes in an unknown manner.

#### 3.3.4.2. Systematic error

Systematic error arises when either incorrect data is used or the model is incomplete. Since systematic errors are not random, therefore they can be removed or reduced by use of better data, or increased accuracy of the model.

#### 3.3.4.3. Random errors

Random errors are created when repeated measurements are performed and each time and under the same condition the results are different, and these results cannot be attributed to a particular reason. Therefore these errors will exist, even if the data and the model are perfect and accurate.

With respect to simulation work, the two error types (systematic and random) provide a convenient mechanism whereby the sources of uncertainty can be classified. The overall uncertainty in a parameter will be the combination of all systematic and random errors. Each uncertainty source has its probability distribution and the overall uncertainty in a parameter used within a simulation will be the sum of these probability distributions. (MacDonald, 2002)

## 3.4. Types of probability distribution

### 3.4.1. Discrete distribution

Discrete distribution can be understood as a probability mass function (probability mass function is a function that gives the probability that a discrete random variable is exactly equal to some value). McDonald (McDonald 2002) explains in discrete distribution each choice shall have a probability of occurrence and the sum total probability of occurrence of all the parameters should be equal to 1:

$$\sum_u \Pr(X = u) = 1 \qquad \text{(eq. 3.1.)}$$

The discrete distribution can either be parametric or non-parametric but for both cases is bounded (i.e. there are a finite number of options). There are many types of parametric distribution (e.g. binomial, etc.) but the non-parametric general discrete distribution, as described here, is of most use in building simulation (McDonald 2002). The discrete distribution requires that each of the possibilities is given a probability of occurrence and that these probabilities sum to one. The difficulty of using this distribution is in specifying the probabilities of the different choices. (McDonald 2002)

### 3.4.2. Even distribution

Even distribution is most useful when working with systematic errors and in this distribution the probability of the variable throughout a possible range is equal.
The even distribution (Evans et al 1993) is a bounded continuous distribution where the probability of the variable taking a value between the bounds is equal. (McDonald 2002)

### 3.4.3. Normal distribution

The normal distribution (Evans et al 1993) is the most appropriate distribution for measured physical data. Typical building simulation examples are measured lengths or temperatures. (McDonald 2002)

As the distribution is unbounded there is a possibility that a normally distributed parameter could have a non-physical value. For example, a measured length is normally distributed but cannot be negative. This is generally unlikely provided the standard deviation is small compared to the mean, as approximately 68% of the probable values that a variable can take are within one standard deviation of the mean value, 95% are within two standard deviations of the mean and 99.5% within 3 standard deviations of the mean. (McDonald 2002)

McDonald (McDonald 2002) explains the normal distribution is one of the most important distributions in the statistics and the distribution is given by:

$$f\ (x;\mu,\ \sigma^2) = (1/(\ \sigma\ (2\pi)^{0.5}) * e^{-0.5((x-\mu)/\sigma)2} \qquad \text{(eq. 3.2.)}$$

Where μ is the mean and σ is the standard deviation. When μ=0 and σ=1 the distribution is known as standard normal distribution. Usually it is assumed that for normally distributed variables, combination of independent normally distributed random variables also distributed according to the normal distribution.

Random number generation for normally distribution function can be done based on different methods e.g. trapezoidal method, polar method, histogram method, box-muller transformation, spline functions, ratio of two uniform deviates, composition-rejection, two terms, center-tail method, composition-rejection, one term and central limit method approach. In this research all of the random numbers have been generated by histogram method.

In this method a histogram with k bins and bin-width c is inscribed under the (folded) normal curve. The difference between the normal curve and the histogram is treated with a combination of triangular distributions and accept-reject method (Walck, 2007). The normal distribution is often called Gaussian distribution or bell curve. The Folded-

Normal and Half-Normal distributions are special cases of normal distribution (McLaughlin, 1999).

### 3.4.4. Log Normal distribution

This distribution is provided when two or more normally distributed parameters being combined to provide a single distribution. The log-normal distribution (Evans et al 1993) is produced when two or more variables which are normally distributed are combined as a product. For example, area which is the result of the product of two length measurements will be log-normally distributed. The distribution cannot produce negative quantities and is unbounded towards positive infinity. (McDonald 2002)
Typical building simulation examples are the metabolic rate and infiltration rate. Note also that for small standard deviations the log-normal distribution can be approximated by the normal distribution. (McDonald 2002)
McDonald (McDonald 2002) explains the log-normal distribution is given by:

$$f\,(x; \mu\,,\ \sigma) = (1/(\ x\sigma\ (2\pi)^{0.5}) * e^{-0.5((\ln x-\mu)/\sigma)2} \quad \text{(eq. 3.3.)}$$

where the variable x>0 and the parameters μ and σ>0 all are real numbers. Also if u is distributed as normal distribution $N(\mu, \sigma^2)$ and u = ln x, then x is distributed according to the log-normal distribution.
The most straightforward way of achieving random numbers from a log-normal distribution is to generate a random number u from a normal distribution with mean μ

and standard deviation σ and construct $r = e^u$ (Walck, 2007). The log-normal distribution is always right-skewed. Log-normal distribution is defined by two parameters of mean and standard deviation in log space. Other used names for log-normal distribution are Cobb-Douglas and anti-log-normal distribution. There are also other forms of log-normal distributions that are characterized by more than two parameters. (McLaughlin, 1999)

### 3.4.5. Triangular distribution

This distribution usually is useful when the choices are minimum, maximum and most likely value of some occurrence.

The triangular distribution (Evans et al 1993) is a bounded continuous distribution. It is often used in fuzzy logic applications and is appropriate here as an intermediate step between the uniform and normal distributions. (McDonald 2002)

In a building simulation context it is a useful distribution because it is described by minimum, maximum and most likely values. For example, the typical occupancy in a space can be augmented by a minimum and maximum occupancy definition to characterize the possible range. (McDonald 2002)

McDonald (McDonald 2002) explains the triangular distribution is given by:

$$f\,(x;\mu\,,\ \Gamma) = (\,-\,|\,x - \mu\,|\,/\,\Gamma^2) + (1/\,\Gamma) \qquad \text{(eq. 3.4.)}$$

Where the variable x is bounded to the interval $\mu - \Gamma <= x <= \mu + \Gamma$ and the distribution and the scale parameters μ and Γ ($\Gamma>0$) all are real numbers. The sum of two pseudorandom numbers uniformly distributed between $(\mu - \Gamma)/2$ and $(\mu + \Gamma)/2$ is distributed according to the triangular distribution. (Walck, 2007)

### 3.4.6. Uniform distribution

Uniform distribution is a sub-category of discrete distribution where a finite number of equally spaced values are equally likely to be observed; in the other word every one of n values has equal probability of occurrence of 1/n.

The distribution places a larger emphasis on extreme values than do the other continuous distributions and so should be used with care. It is most useful in simulation where attention should be drawn to a poorly defined parameter, say at the early design stage. The distribution is the most suitable for modeling systematic errors as these errors are not random and hence the true value is equally probable throughout the given range. Typical uses of the even distribution could be for casual gains from occupants, or the conductivity of a hygroscopic material. (McDonald 2002)

## 3.5. Current state of building simulation uncertainty in literature

Starting in the late 80's and since then several research studies have been performed to investigate the effects of input uncertainty, on uncertainty in the output of building simulations, with the target of creating performance indicators for the buildings. Multiple papers were published by Augenbroe, de Wilde (De Wilde et al. 2001), Clarke et al. (1990), Fürbringer (1994), Lomas (1993), Jensen (1994), Wijsman (1994), De Wit

(1997). Based on Wit et Augenbroe (2001) most of these research has been focused on effects of spread of material properties and building dimensions on simulation outcome, but modeling uncertainties have received only limited attention, and virtually no concern has been given to the question how quantitative uncertainty can be used to better inform a design decision.

Malkawi and Augenbroe (2003) presented that uncertainty may enter the assessment of building performance from, (1) design specifications, (2) physical model development, (3) numerical errors and (4) scenario.

Moon and Augenbroe (2005) presented a new approach for analyzing mold growth risk in buildings, based on a mixed simulation approach with consideration of uncertainties in relevant building parameters. Their approach was capable of predicting and explaining mold growth occurrences that would typically not show up in standard deterministic simulations.

Devki (2006) presented a guide for calculating the uncertainty in testing of on-site chillers performances caused by accuracy margin in testing instrument.

Petr et al (2007) presented that it is necessary to estimate uncertainty in building performance simulation, and uncertainty for the HVAC system can bring mishmash in controls of heating and cooling coils. The sensitivity analysis is important for finding out the most influential input parameter, which can be further optimized. And upon the whole this kind of process is way how to reduce energy consumption.

In the same year two researchers (Yan et Jiang, 2007) showed the inner heat gains acts in an uncertain way in time serial and space. They showed that presently, fixed schedule is generally used to describe the inner heat gains in the state of art HVAC system simulation which couldn't reflect the uncertain characteristic of internal heat gains.

In "Ernest Orlando Lawrence Berkeley National Laboratory" researchers (Walker et al., 2010) used the various analysis techniques applied to the calculation procedure and presented estimates of uncertainty in measured duct leakage.

In 2011 in a published paper (Eisenhower et al. 2011), authors explained an effort to create a data base that contains the top 10% most influential parameters in each building type.

An extensive NSF-EFRI funded research effort started in 2010 by Augenbroe and a group of faculty and PhD students at the Georgia Institute of Technology targets the development of risk conscious design and retrofit of buildings. The project is expected to develop a new generation of rigorously quantified parameter uncertainties and new ways to use them in a novel uncertainty analysis workbench.

# CHAPTER 4

# HVAC SYSTEMS

Before analyzing the effects of equipment test tolerance in cooling systems it is essential to become familiar with different systems and its energy consuming components. In this section we will briefly explain how some common cooling systems work. For a more detail description of different HVAC systems refer to ASHRAE handbook 2008 “HVAC systems and equipment” and Trane trace 700 software system library, produced by Trane company.

An air-conditioning system maintains desired environmental conditions within a space. In almost every application, there is a myriad of options available to the designer to satisfy this basic goal (ASHRAE Handbook, 2008). Mechanical system selection is as much art as science. The choice that the designer makes must balance a wide range of issues including first cost, energy cost, maintenance effort and cost, coordination with other trades, spatial requirement, acoustics, flexibility, architectural aesthetics, and many other issues. (Pacific Gas and Electric Company -2007)

Many different factors including, but not limited to, conditioning of the space must be considered by the designer in order to provide the most suitable system for each specific application. Among these factors the one with the higher degree of importance is supporting specific functions that come with the different applications, such as serving a clean room in a manufacturing site, an auditorium in an educational facility, or an intensive care room in a hospital. In the commercial world, we can specify numerous types of applications, but for the purpose of our research we will concentrate on two popular applications of office buildings, and healthcare facilities.

Air conditioning systems are categorized by the method used to control cooling in the conditioned area (ASHRAE Handbook, 2008). Different reference resources categorize these systems differently, but the most dominant methods to categorize the systems and also promoted by ASHRAE systems handbook is to divide them into centralized and decentralized systems, or all air, air and water and all water systems.

The dictionary definition of efficiency is the ratio of the effective or useful output to the total input in any system. The Air Conditioning and Refrigeration Institute (ARI) is an institute that regulates how each manufacturer has to perform and to publish the efficiency of its products, compared to the minimum allowable by the testing agencies guidelines. The published values shall describe the efficiency of the equipment under full and different part load conditions. The efficiency of different equipments is described usually with the ratio of the usable output to the consumed input energy. For example the efficiency of a fan can be described in the form of the ratio between power transferred to the airflow and the power used by the fan.

To ensure receiving high performances from the cooling systems, different reference books have offered different prescriptive guidance, e.g. needed workmanship for construction materials, control strategies to be implemented and of course individual equipment efficiencies. These sources have also suggested performing simulations of (building energy model) in order to ensure a minimum acceptable performance for the building.

One of the more dominant methods of energy efficiency modeling is structured in ANSI/IESNA/ASHRAE Standard 90.1-2010 which in order to specify the energy efficiency of the building during the design phase requires to perform either a performance based analysis or to run a simulation based modeling of the building under construction and to compare these results against the results from an imaginary equivalent building that is performing with baseline recommended HVAC system along with other basic building features. The amount of saved energy in design building compared to the imaginary building will be selected as the degree of energy efficiency of the proposed building.

Simulation software computes the yearly energy consumption for the specific building in a specific climate under full and part load condition of the HVAC system among other related criteria. But there are some other major considerations that can affect the overall efficiency of a system as well. These considerations cannot be translated into quantitative measure easily and almost all of the simulation software packages lack the capacity to include these parameters in their final analysis. Considerations such as acoustical impact, space saving and degree of affecting other trades are in this category. To include such parameters in the overall system efficiency the most usual method is relying on expert interview results as well as literature research.

In the continuation of this chapter we will provide an informational review of some of the most dominant cooling systems and its energy consuming parts.

## 4.1. A brief review of the most applicable cooling systems

In this section we will review the most applicable cooling systems as they are being utilized for conditioning of the commercial buildings specifically for office buildings and healthcare facilities.

### 4.1.1. Chilled water systems

A chilled water system uses chilled water to absorb heat from the inside of the building (cooling coil at main air handling unit) and transfers it to the outdoor via a water cooled (cooling tower and pumps; Figure 1A) or air cooled (Figure 1B) chiller assembly. Chilled water systems are usually being utilized in the larger systems because they are more efficient than the alternatives. Chillers are usually built and tested as packaged units in the factory thereby decreasing field labor, and improving the system reliability due to reduction of the field labor. It also helps to keep the refrigerant in a central location, which in return simplifies the protection against refrigerant leak.

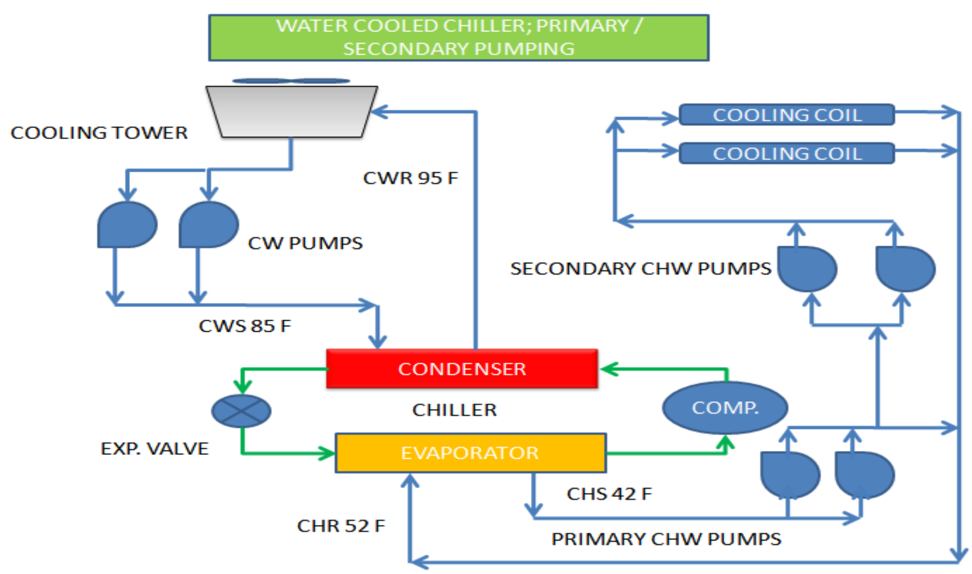


Figure 4.1A: Water Cooled Chilled Water system

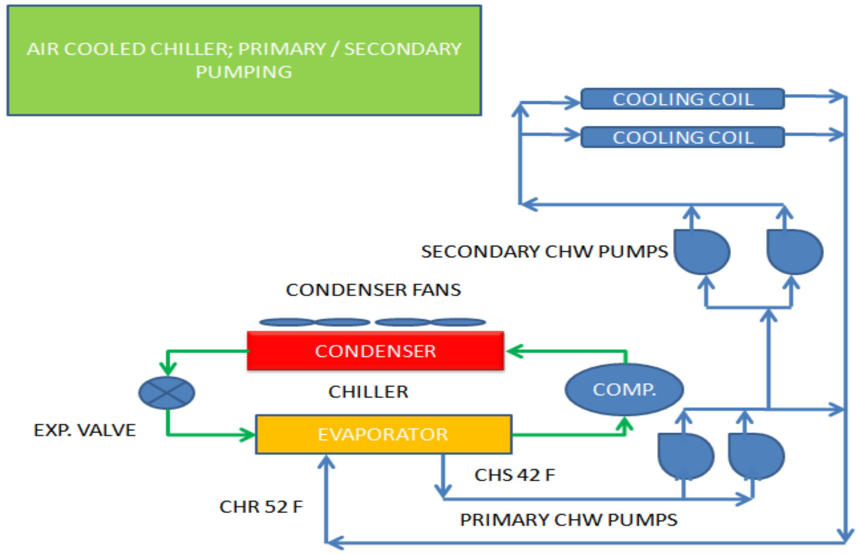


Figure 4.1B: Air Cooled Chilled Water system

The main sources of mechanical energy consumption in Air/ Water cooled chilled water systems in the power required for running the chiller (compressor and condenser), power required for running the fan at cooling tower (Condenser fans in air cooled system), and power required to run the pumps. Heat transfer from pipes can indirectly increase the energy consumption of the system also. Minor energy is consumed by low voltage power provided for control valves another source of energy consumption.

### 4.1.2. Direct Expansion (DX) Unitary systems

In a direct-expansion unitary system, the evaporator is in direct contact with the air stream, so the cooling coil of the airside loop is also the evaporator of the refrigeration loop. The main reason for using this type system is lower cost due to less required labor and also fewer components to install. The most important factors that affect the decision to select DX versus chilled water system are: Installed cost, space requirements, building size, system capacity, and controls.

The main sources of mechanical energy consumption in DX system in cooling season are power required for running the DX system compressor, power required for running the supply and return fans (if it is provided), and power required for running the terminal unit fans. Minor energy is consumed by low voltage power provided for control valves is another source of energy consumption.

### 4.1.3. Variable Volume Package Rooftop Unit

This system is constructed of a fan(s), direct expansion cooling coil that absorb the heat from the inside and reject that heat to the outside via condenser fans. There is no need for a separate chiller, chilled water pumps, cooling tower, and condenser water pumps in this arrangement. Supply fan delivers a variable air volume to the terminal units and return/exhaust fan modulate in track with the supply air to provide a proper air balance in the building.

The main energy consumers in the system are supply fan power input, return fan (if it is provided) power input, compressor power input, condenser fans power input, and terminal units fan power input.

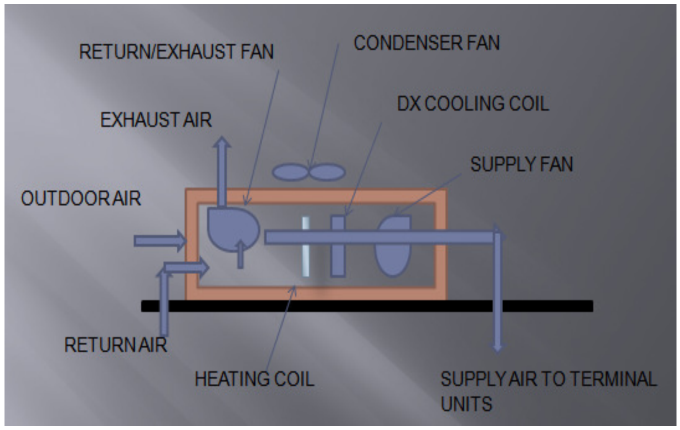


Figure 4.2: Variable Volume Package Rooftop Unit

### 4.1.4. Self-Contained Water-Cooled Air Conditioner

This system is constructed of a fan(s), direct expansion cooling coil that absorb the heat from the inside and reject that heat to the condenser water loop, cooling tower and condenser water pumps. There is no need for a separate chiller, and chilled water pumps in this arrangement. Supply fan delivers a variable air volume to the terminal units and return/exhaust fan modulate in track with the supply air to provide a proper air balance in the building.

The main energy consumers in the system are supply fan power input, return fan (if it is provided) power input, compressor power input, terminal units fan power input.

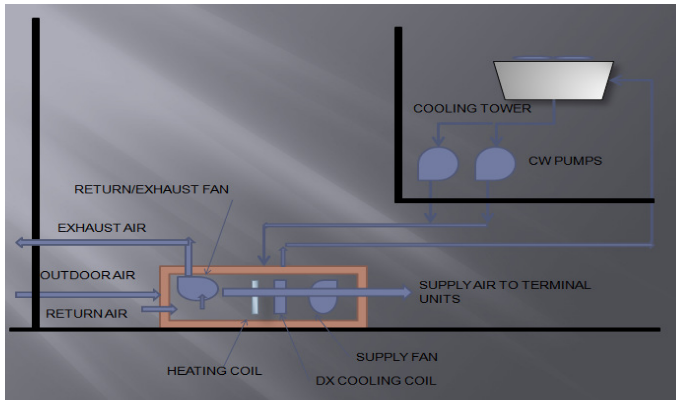


Figure 4.3: Self-Contained Water-Cooled Air Conditioner

### 4.1.5. Packaged Terminal Air Conditioner

A separate Packaged Terminal Air Conditioner (PTAC) including a fan, filter, direct expansion cooling coil, and hot water/ electric heating coil if it is needed is located in each room. The unit supplies a constant volume of conditioned air to the room and the coils control valves modulate to meet the varying load.

The sources of mechanical energy consumption are supply fan motor input power, electric heating coil and compressor and condenser power input.

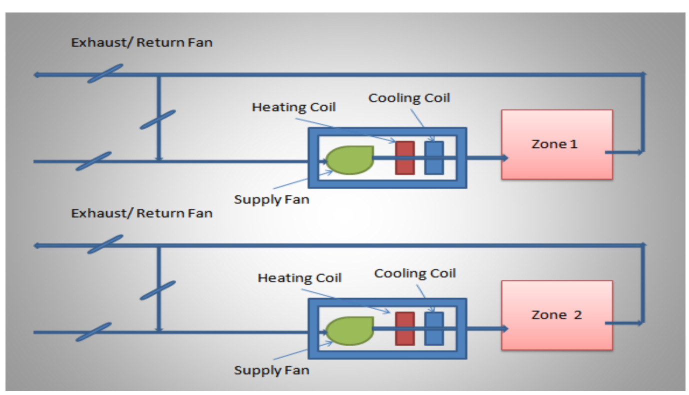


Figure 4.4: Packaged Terminal Air Conditioner

### 4.1.6. Water Source Heat Pump

In this system an individual constant volume cooling/heating heat pump is dedicated to each thermal zone, and as the zone load varies, unit modulates to match the heating/ cooling requirements. Any time the zone temperature moves above the zone cooling temperature set-point, the cooling coil will be energized and delivers a constant temperature cooling supply air to cool the room. The removed heat from the space is then rejected to the condenser water loop. During times that there is no need for running the cooling coil, a constant volume air with a temperature of equal to the mixture of return and outdoor air is delivered to the zone.

The sources of mechanical energy consumption in cooling season in this type of systems are supply fan motor input power, exhaust fan motor input power (if it is required), electric preheat/ reheat coil, and compressor power input. Duct air leakage, heat transfer from ducts, and efficiency loss in water coils are other sources that can indirectly increase the energy consumption of the system. Minor energy is consumed by low voltage power provided for control valves and dampers is the other source of energy consumption.

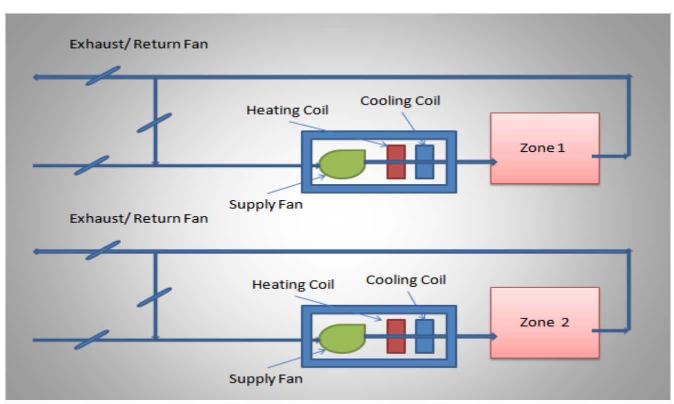


Figure 4.5: Water Source Heat Pump or Incremental Heat Pump

## 4.2. Airside Systems:

### 4.2.1. Variable Air Volume system with Parallel Fan Powered Units

This system consists of a central, variable volume supply fan that supplies conditioned air to all the local parallel fan-powered variable air volume terminal units through a network of medium pressure supply ducts. Quantity and mixture of the air which is provided for each room is calculated based on the room sensible cooling load, the needed outdoor air flow requirement, and thermostat setting. A variable frequency drive is used to modulate the air handling unit supply fan to provide required airflows which in each instant is equal to the sum of all the terminal unit's primary airflows. This primary air then will be mixed with some of the plenum air through the terminal unit constant volume fan before introduction to the room. (Terminal units are also equipped with reheat coils (hot water or electrical) for the heating season, and dehumidification of sensitive spaces if it is required during the cooling season).

The sources of mechanical energy consumption in cooling season in this system are supply fan motor input power, return fan motor input power, terminal unit fan motor input power, electric preheat coil (if it is used for freeze protection instead of hot water coil) in air handling unit and electric reheat (if it is used for dehumidification instead of hot water coil). Duct air leakage, heat transfer from ducts, and efficiency loss in water coils are other sources that can indirectly increase the energy consumption of the system. Minor energy is consumed by the low voltage power provided for control valves and dampers, and the power input to the variable frequency drives for supply and return fans that can be factored in supply and return fan consumption itself are the other sources of energy consumption.

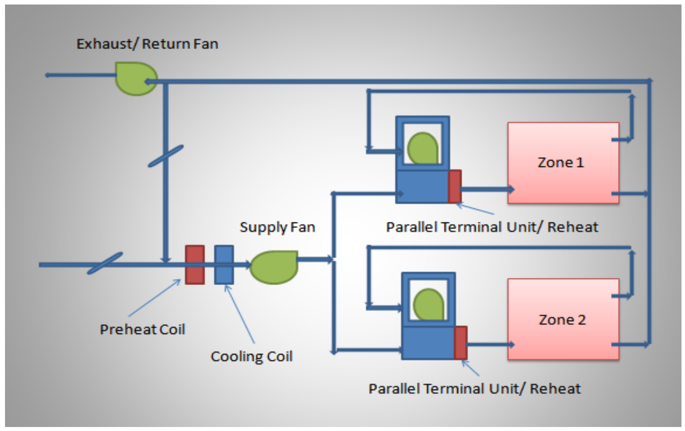


Figure 4.6: Parallel Fan Powered VAV, HTG Coil on Mixing Box Outlet

### 4.2.2. Constant Air Volume system with Bypass Variable Air Volume terminal units with Reheat

This system is consists of a central, constant volume supply fan that supplies conditioned air to all the local variable air volume terminal boxes through a network of medium pressure supply ducts. Quantity of the air which is sent to each space is based on the space sensible cooling load, the needed outdoor air flow requirement, and thermostat setting. Air that is not needed for cooling the space is bypassed into a common return air path and after mixing with the return air from all the other spaces goes back to the air handling unit (Terminal units are also equipped with reheat coils (hot water or electrical) for the heating season, and dehumidification of sensitive spaces if it is required during the cooling season).

The sources of mechanical energy consumption in cooling season in this type of systems are supply fan motor input power, return fan motor input power, electric preheat coil (if it is used for freeze protection instead of hot water coil) in air handling unit and electric reheat (if it is used for dehumidification instead of hot water coil). Duct air leakage, heat transfer from ducts, and efficiency loss in water coils are other sources that can indirectly increase the energy consumption of the system. Minor energy is consumed by the low voltage power provided for control valves and dampers is the other source of energy consumption.

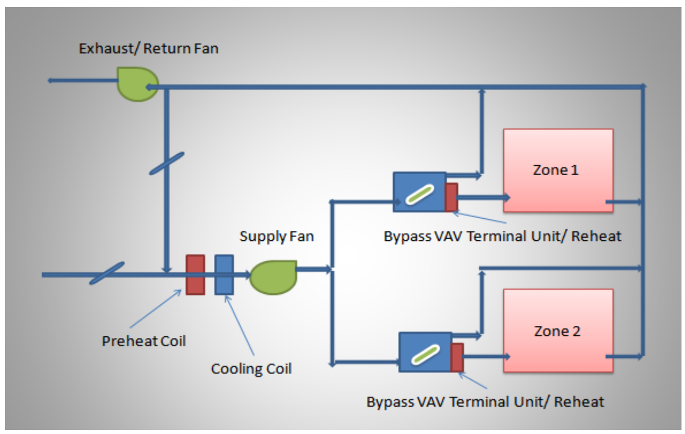


Figure 4.7: Bypass VAV with Reheat

### 4.2.3. Variable Air Volume system with Variable Volume Terminal Units with Reheat

This system is made of a central, variable volume supply fan that supplies conditioned air to all the room's variable air volume terminal units through a medium pressure duct. The quantity of the air which is sent to each room is based on the room's sensible cooling load, the needed outdoor air flow requirement and thermostat setting. A variable frequency drive modulates the supply fan in proportion to provide air flow equal to the sum of all the terminal units airflow. (Terminal units are also equipped with reheat coils (hot water or electrical) for the heating season, and dehumidification of sensitive spaces if it is required during the cooling season).

The sources of mechanical energy consumption in cooling season in this type of systems are supply fan motor input power, return fan motor input power, electric preheat coil (if it is used for freeze protection instead of hot water coil) in air handling unit and electric reheat (if it is used for dehumidification instead of hot water coil). Duct air leakage, heat transfer from ducts, and efficiency loss in water coils are other sources that can indirectly increase the energy consumption of the system. Minor energy is consumed by the low voltage power provided for control valves and dampers is the other source of energy consumption.

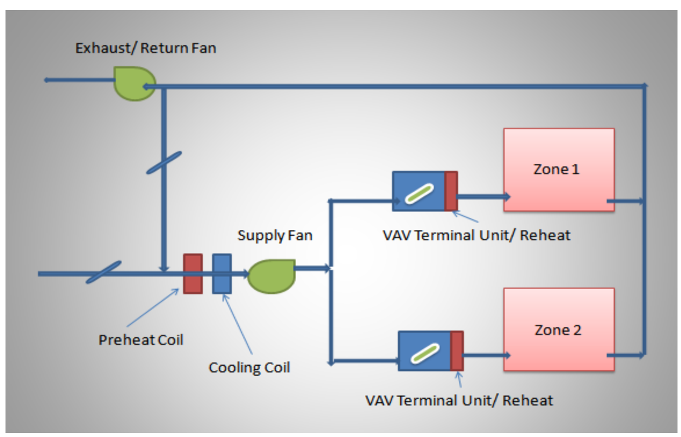


Figure 4.8: Variable Volume Reheat

### 4.2.4. Variable Air Volume system with Series Fan-Powered Units

This system is made up of a central, variable volume supply fan that supplies conditioned air to all the room's series fan-powered VAV terminal units through medium pressure ducts. Each room will receive a constant quantity of air. A variable frequency drive modulates the supply fan in proper proportions to provide air flow equal to the sum of the terminal unit's primary airflows. Each terminal unit box is equipped with a constant volume fan that draws plenum air into the terminal unit box and mixes it with the primary air before delivering a constant quantity of air flow into the room. ( Terminal units are also equipped with reheat coils (hot water or electrical ) for the heating season, and dehumidification of sensitive spaces if it is required during the cooling season).

The sources of mechanical energy consumption in the cooling season in this type of systems are supply fan motor input power, return fan motor input power, terminal unit fan motor input power, electric preheat coil (if it is used for freeze protection instead of hot water coil) in air handling unit and electric reheat (if it is used for dehumidification instead of hot water coil). Duct air leakage, heat transfer from ducts, and efficiency loss in water coils are other sources that can indirectly increase the energy consumption of the system. Minor energy is consumed by low voltage power provided for control valves and dampers, and the power input to the variable frequency drives for supply and return fans that can be factored in supply and return fan consumption itself are the other sources of energy consumption.

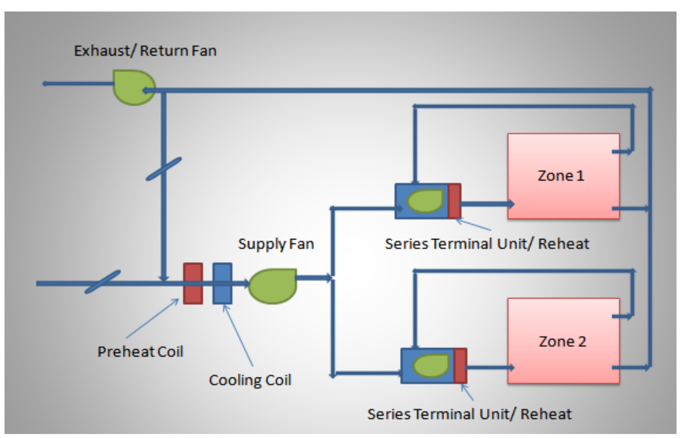


Figure 4.9: Series Fan-Powered VAV

### 4.2.5. Two-Fan Double Duct VAV

This system is made up of a separate cold path and a separate hot path that provide cold and hot air, respectively, to all room's terminal mixing units through medium pressure ducts. The cooling and heating supply fans are both variable volume and will modulate to provide a proper flow mixture to the terminal mixing units and rooms. A heating supply fan re-circulates the zones return air for mixing with cold path supply air. Terminal mixing unit minimum flow is used to determine cold path airflow into the room’s mixing unit. ( Terminal units are also equipped with reheat coils (hot water or electrical) for the heating season, and dehumidification of sensitive spaces if it is required during the cooling season ).

The sources of mechanical energy consumption in cooling season in this type of systems are supply fan motor input power, return fan motor input power, electric preheat coil (if it is used for freeze protection instead of hot water coil) in air handling unit and electric reheat (if it is used for dehumidification instead of hot water coil). Duct air leakage, heat transfer from ducts, and efficiency loss in water coils are other sources that can indirectly increase the energy consumption of the system. Minor energy is consumed by low voltage power provided for control valves and dampers is the other source of energy consumption.

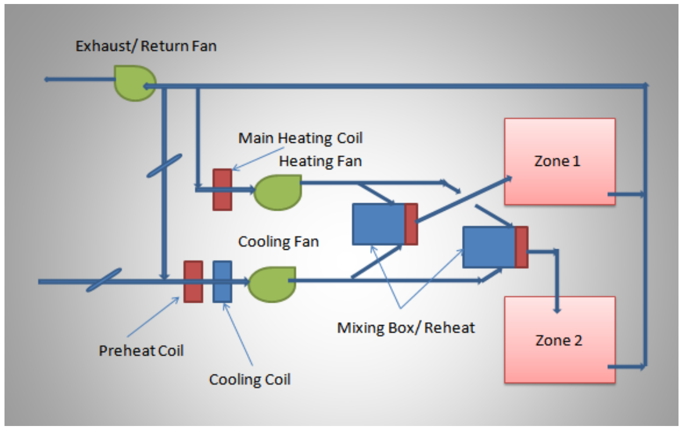


Figure 4.10: Two-Fan Double Duct VAV

### 4.2.6. Changeover Bypass VAV

The difference between this system and bypass variable air volume system is that in the latter each terminal unit bypasses the air individually, but in this system bypassing is done through a designated bypass variable air volume box.

The sources of mechanical energy consumption in cooling season in this type of systems are supply fan motor input power, return fan motor input power electric preheat coil (if it is used for freeze protection instead of hot water coil) in air handling unit and electric reheat (if it is used for dehumidification instead of hot water coil). Duct air leakage, heat transfer from ducts, and efficiency loss in water coils are other sources that can indirectly increase the energy consumption of the system. Minor energy is consumed by low voltage power provided for control valves and dampers is the other source of energy consumption.

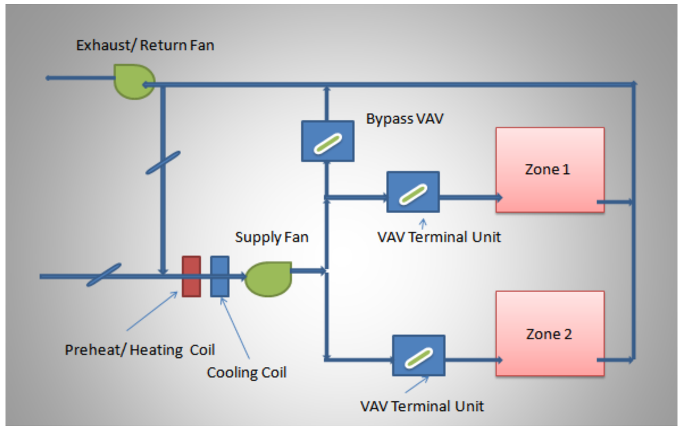


Figure 4.11: Changeover Bypass VAV

### 4.2.7. Fan Coil or Unit Ventilator

A separate fan coil unit or unit ventilator (including a fan, filter, cooling coil, and heating coil) is located in each zone. Central heating and cooling plants provide required heating and cooling for the respected coil (chilled water, hot water or steam). Basically the unit supplies a constant quantity of conditioned air to the zone and the coils control valves modulate to meet the varying load. In large systems, dedicated outdoor air units will deliver pre-heated/ pre-cooled outside air through a network of ductworks to the mixing air plenum installed in the back of the fan coil units, which mixes this outside air with the return air from the room before moving the mixed air through the fan coil fan.

The sources of mechanical energy consumption in cooling season in this type of systems are supply fan motor input power including the outdoor air unit supply fan (if it is used), exhaust fan motor input power, and electric heat coil (if it is used instead of hot water coil) in fan coil unit. Duct air leakage, heat transfer from ducts, and efficiency loss in water coils are other sources that can indirectly increase the energy consumption of the system. Minor energy is consumption made by low voltage power input for the control valves and dampers is the other source of energy consumption.

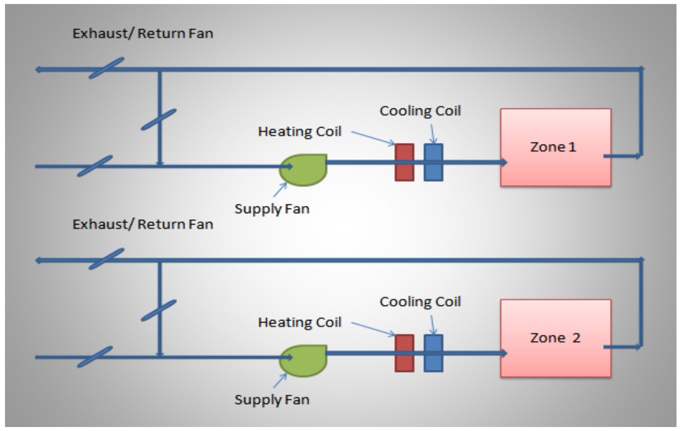


Figure 4.12: Fan Coil or Unit Ventilator

### 4.2.8. Double Duct

A constant volume fan delivers air to two ducts (one cold line and one hot line) where cooling coil is installed on the cold line and heating coil is installed on hot line. Fan receives a mixture of outdoor air and return air from a common return path. Each terminal unit will receive a mixture of cold and hot air (if required), mixes them in a proper portion and delivers a constant volume air to the room to satisfy the room load. The sources of mechanical energy consumption in cooling season in this type of systems are supply fan motor input power, return fan motor input power, electric preheat coil (if it is used for freeze protection instead of hot water coil) in air handling unit and electric reheat (if it is used for dehumidification instead of hot water coil). Duct air leakage, heat transfer from ducts, and efficiency loss in water coils are other sources that can indirectly increase the energy consumption of the system. Minor energy is consumed by low voltage power provided for control valves and dampers is the other source of energy consumption.

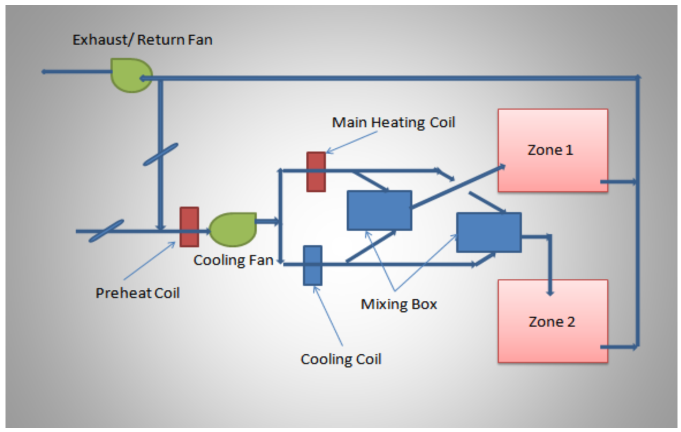


Figure 4.13: Double Duct

### 4.2.9. Rooftop Multi-zone

A constant volume fan delivers air to two ducts (one cold line and one hot line) where the cooling coil is installed on the cold line and heating coil is installed on the hot line. The fan pulls a mixture of outdoor air and return air from a common return path and supply the mixture to two cold and hot lines with proper portions. Each terminal unit then will receive a mixture of cold and hot air (if required), mixes them in a proper portion and delivers a constant volume air to the room to satisfy the room load.

The sources of mechanical energy consumption in cooling season in this type of systems are supply fan motor input power, return fan motor input power, electric preheat coil (if it is used for freeze protection instead of hot water coil) in air handling unit and main electric reheat (if it is used for dehumidification instead of hot water coil). Duct air leakage, heat transfer from ducts, and efficiency loss in water coils are other sources that can indirectly increase the energy consumption of the system. Minor energy is consumed by low voltage power provided for control valves and dampers is the other source of energy consumption.

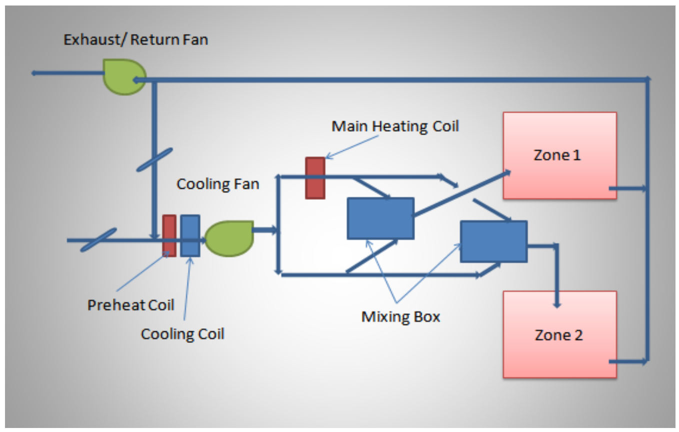


Figure 4.14: Rooftop Multi-zone

### 4.2.10. Under-floor Air Distribution CV

Under-floor air distribution systems, originally were used in the 1950s in spaces with high heat loads such as computer rooms, and experience has shown it is one of the most effective methods of providing localized cooling.

An under-floor air distribution system (UFAD) uses the open space (under floor plenum) between the structure slab and the underside of a raised floor system to deliver conditioned air to supply outlets located at or near floor level within the occupied zone 9up to 6 –ft height) of the space. (Bauman, 2003)

This system is similar to a Variable-Temperature, Constant-Volume system, except that 1) instead of the duct, it uses the under-floor plenum as the path of the delivering air, 2) a return-air bypass arrangement is used upstream of the fan to provide sufficient dehumidification without the need for reheat coil, and 3) space heating is delivered by a baseboard radiator or convector. In cooling mode, supply air will be introduced to the room with a higher temperature (usually around 63F instead of normally 55 F in regular systems) and lower speed to prevent occupant discomfort. ASHRAE 55 allows a maximum vertical air temperature difference of 5 degrees F between heights of 67 in. and 4 in. Research by (Fisk et al. 1991) has shown that under-floor air distribution systems that use floor diffusers can provide modestly higher performance compared to overhead mixing systems.

When the room sensible load decreases the supply air temperature rises and therefore cooling consumption decreases.

The sources of mechanical energy consumption in cooling season in this type of systems are supply fan motor input power, return fan motor input power, electric preheat coil (if it is used for freeze protection instead of hot water coil) in air handling unit and baseboard electric heat (if it is used). Duct air leakage, heat transfer from ducts, and efficiency loss in water coils are other sources that can indirectly increase the energy consumption of the system. Minor energy is consumed by low voltage power provided for control valves and dampers is the other source of energy consumption.

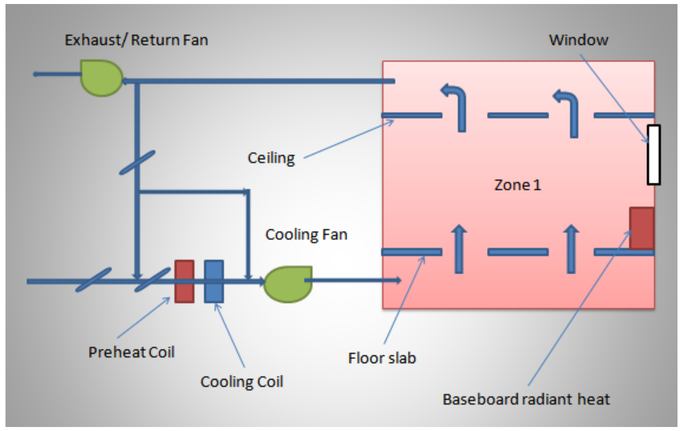


Figure 4.15: Under-floor Air Distribution CV

#### 4.2.11. Under-floor Air Distribution Parallel Fan-Powered VAV

This system is similar to a parallel, fan-powered variable air volume system, except that 1) instead of the duct, it uses the under-floor path as the source of the delivering air, 2) a return-air bypass arrangement is used upstream of the fan to provide sufficient dehumidification without the need for reheat, and 3) space heating is supplied by an under-floor variable air volume terminal that draws air from the room rather than the ceiling plenum. In cooling mode, supply air will be introduce to the room with a higher temperature (usually around 63F instead of normally 55 F in regular systems) and lower speed to prevent occupant discomfort.

The sources of mechanical energy consumption in cooling season in this type of systems are supply fan motor input power, return fan motor input power, terminal unit fan motor input power, electric preheat coil (if it is used for freeze protection instead of hot water coil) in air handling unit and electric reheat (if it is used for dehumidification instead of hot water coil). Duct air leakage, heat transfer from ducts, and efficiency loss in water coils are other sources that can indirectly increase the energy consumption of the system. Minor energy is consumed by low voltage power provided for control valves and dampers, and the power input to the variable frequency drives for supply and return fans that can be factored in supply and return fan consumption itself are the other sources of energy consumption.

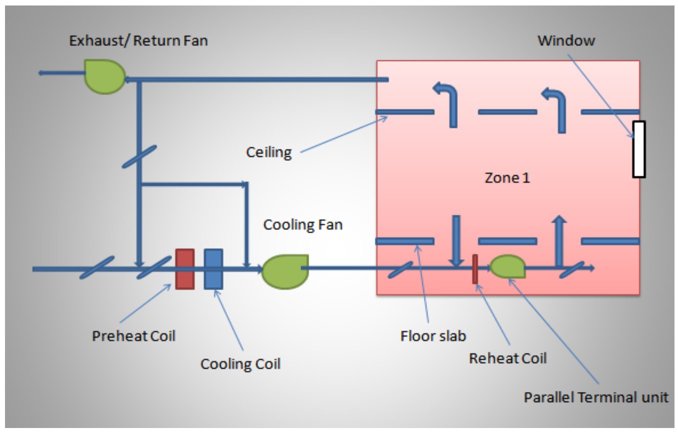


Figure 4.16: Under-floor Air Distribution Parallel Fan-Powered VAV

### 4.2.12. Under-floor Air Distribution Series, Fan-Powered VAV

This system is similar to a series, fan-powered variable air volume system, except that 1) instead of the duct, it uses the under-floor path as the source of the delivering air, 2) a return-air bypass arrangement is used upstream of the fan to provide sufficient dehumidification without the need for reheat, and 3) space heating is supplied by an under-floor variable air volume terminal that draws air from the room rather than the ceiling plenum. In cooling mode, supply air will be introduce to the room with a higher temperature (usually around 63F instead of normally 55 F in regular systems) and lower speed to prevent occupant discomfort.

The sources of mechanical energy consumption in cooling season in this type of systems are supply fan motor input power, return fan motor input power, terminal unit fan motor input power, electric preheat coil (if it is used for freeze protection instead of hot water coil) in air handling unit and electric reheat (if it is used for dehumidification instead of hot water coil). Duct air leakage, heat transfer from ducts, and efficiency loss in water coils are other sources that can indirectly increase the energy consumption of the system. Minor energy is consumed by low voltage power provided for control valves and dampers, and the power input to the variable frequency drives for supply and return fans that can be factored in supply and return fan consumption itself are the other sources of energy consumption.

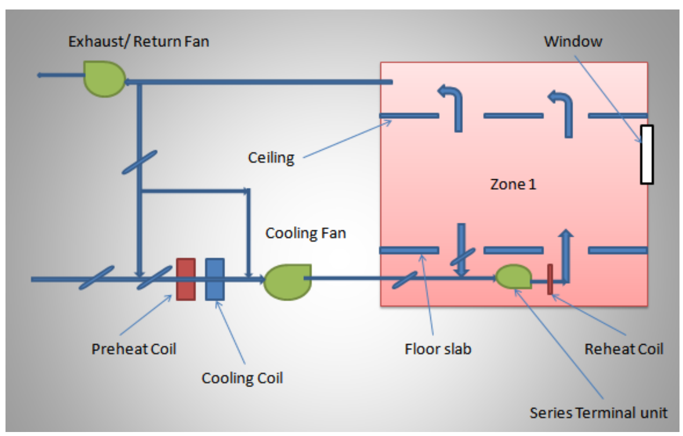


Figure 4.17: Under-floor Air Distribution Series, Fan-Powered VAV

### 4.2.13. UFAD VAV w/Baseboard Heating

This system is similar to a variable air volume system with baseboard heat, except that 1) instead of duct the supply air is delivered via an under-floor path and 2) a return-air bypass arrangement is assumed in order to provide sufficient dehumidification without the need for reheat.

In cooling mode, supply air will be introduce to the room with a higher temperature (usually around 63F instead of normally 55 F in regular systems) and lower speed to prevent occupant discomfort.

The sources of mechanical energy consumption in cooling season in this type of systems are supply fan motor input power, return fan motor input power, electric preheat coil (if it is used for freeze protection instead of hot water coil) in air handling unit and electric baseboard reheat (if it is used for dehumidification instead of hot water coil). Duct air leakage, heat transfer from ducts, and efficiency loss in water coils are other sources that can indirectly increase the energy consumption of the system. Minor energy is consumed by low voltage power provided for control valves and dampers, and the power input to the variable frequency drives for supply and return fans that can be factored in supply and return fan consumption itself are the other sources of energy consumption.

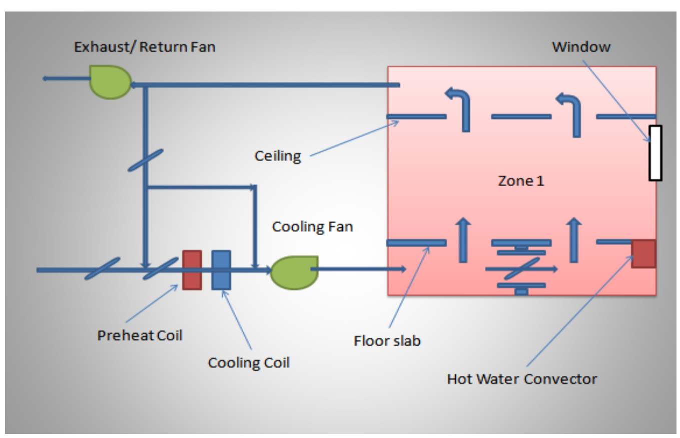


Figure 4.18: UFAD VAV w/Baseboard Heating

### 4.2.14. UFAD VAV w/Fan-Assisted Reheat

This system is similar to a VAV Reheat system, except that 1) the supply air is delivered via an under-floor path, 2) a return-air bypass arrangement is assumed in order to provide sufficient dehumidification without the need for reheat, and 3) space heating is supplied by an under-floor terminal that uses a small fan (Secondary Fan) to draw air from the floor through a heating coil.

In cooling mode, supply air will be introduce to the room with a higher temperature (usually around 63F instead of normally 55 F in regular systems) and lower speed to prevent occupant discomfort.

The sources of mechanical energy consumption in cooling season in this type of systems are supply fan motor input power, return fan motor input power, terminal unit fan motor input power, electric preheat coil (if it is used for freeze protection instead of hot water coil) in air handling unit and electric reheat (if it is used for dehumidification instead of hot water coil). Duct air leakage, heat transfer from ducts, and efficiency loss in water coils are other sources that can indirectly increase the energy consumption of the system. Minor energy is consumed by low voltage power provided for control valves and dampers, and the power input to the variable frequency drives for supply and return fans that can be factored in supply and return fan consumption itself are the other sources of energy consumption.

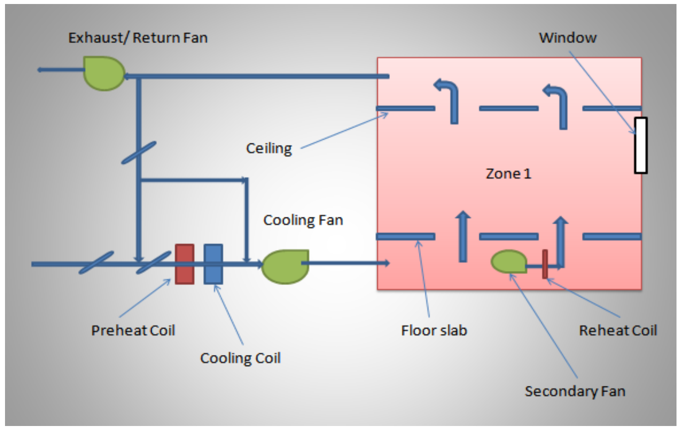


Figure 4.19: UFAD VAV w/Fan-Assisted Reheat

### 4.2.15. Displacement Ventilation CV

Displacement ventilation has been used quite commonly in Scandinavia during the past twenty years. It was first applied to the welding industry in 1978 and has since been increasingly used as a means of ventilation in industrial facilities to provide god indoor air quality and save energy (Chen et Glicksman, 2003).

In cooling mode, supply air will be introduce to the room through wall-mounted sidewall diffusers with a higher temperature (usually around 63F instead of normally 55 F in regular systems) and lower speed to prevent occupant discomfort. As per Chen (Chen et Glicksman, 2003) the design air temperature between the head and foot level of a sedentary occupant should be less than 3.6 degree F in order to maintain a comfort level. Low velocity air moves across the floor and as it gets in touch with heat sources (people, equipment, etc.) warms up (usually it is considered that the air gets warmer about 1 degree F per 1 vertical foot) and moves up due to natural buoyancy and convection.

When the room sensible load decreases the supply air temperature rises and therefore cooling consumption decreases.

The sources of mechanical energy consumption in cooling season in this type of systems are supply fan motor input power, return fan motor input power, electric preheat coil (if it is used for freeze protection instead of hot water coil) in air handling unit and electric baseboard reheat (if it is used for dehumidification instead of hot water coil). Duct air leakage, heat transfer from ducts, and efficiency loss in water coils are other sources that can indirectly increase the energy consumption of the system. Minor energy is consumed by low voltage power provided for control valves and dampers is the other sources of energy consumption.

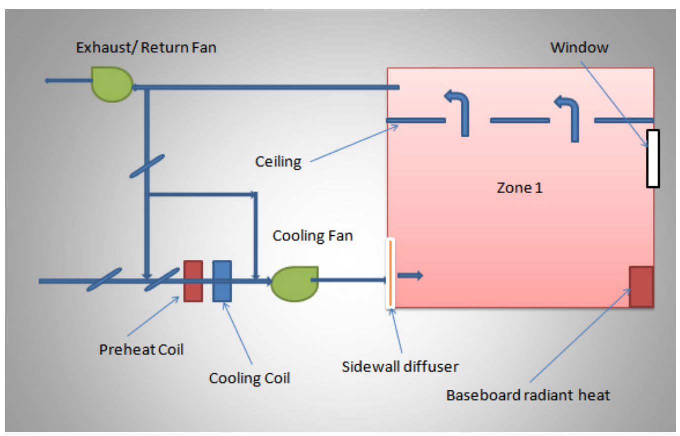


Figure 4.20: Displacement Ventilation CV

### 4.2.16. Displacement Ventilation VAV

This system is similar to a variable air volume system with baseboard heat, except that 1) instead of duct the supply air is delivered via an under-floor path and 2) a return-air bypass arrangement is assumed in order to provide sufficient dehumidification without the need for reheat.

In cooling mode, supply air will be introduced to the room with a higher temperature (usually around 63F instead of normally 55 F in regular systems and lower speed to prevent occupant discomfort. Air entrance to the room is being controlled by modulating air damper at terminal boxes as it is controlled by the space temperature sensor.

The sources of mechanical energy consumption in cooling season in this type of systems are supply fan motor input power, return fan motor input power, electric preheat coil (if it is used for freeze protection instead of hot water coil) in air handling unit and electric baseboard reheat (if it is used for dehumidification instead of hot water coil). Duct air leakage, heat transfer from ducts, and efficiency loss in water coils are other sources that can indirectly increase the energy consumption of the system. Minor energy is consumed by low voltage power provided for control valves and dampers, and the power input to the variable frequency drives for supply and return fans that can be factored in supply and return fan consumption itself are the other sources of energy consumption.

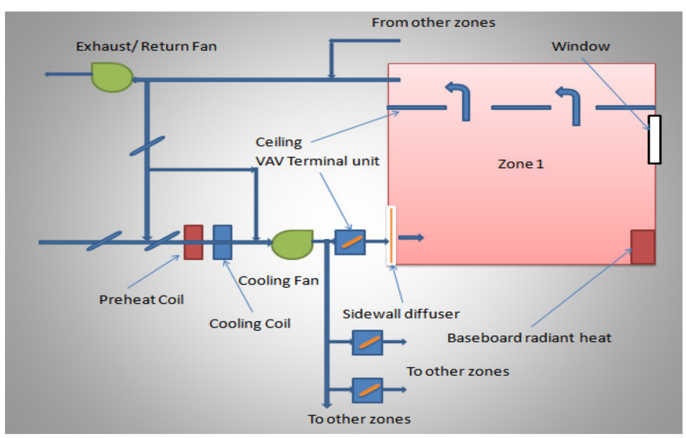


Figure 4.21: Displacement Ventilation VAV

### 4.2.17. Displacement Ventilation w/Chilled Ceilings

In cooling mode, supply air will be introduced to the room with a higher temperature (usually around 63F instead of normally 55 F in regular systems) and lower speed to prevent occupant discomfort. A modulating damper varies the amount of air introduced to the room based on the space temperature sensor. If still there is need for further cooling, chilled ceiling panels will pick up the rest of the load. A return air bypass arrangement helps to provide dehumidification without the need for reheat.

The sources of mechanical energy consumption in cooling season in this type of systems are supply fan motor input power, return fan motor input power, electric preheat coil (if it is used for freeze protection instead of hot water coil) in air handling unit and electric baseboard reheat (if it is used for dehumidification instead of hot water coil). Duct air leakage, heat transfer from ducts, and efficiency loss in water coils are other sources that can indirectly increase the energy consumption of the system. Minor energy is consumed by low voltage power provided for control valves and dampers, and the power input to the variable frequency drives for supply and return fans that can be factored in supply and return fan consumption itself are the other sources of energy consumption.

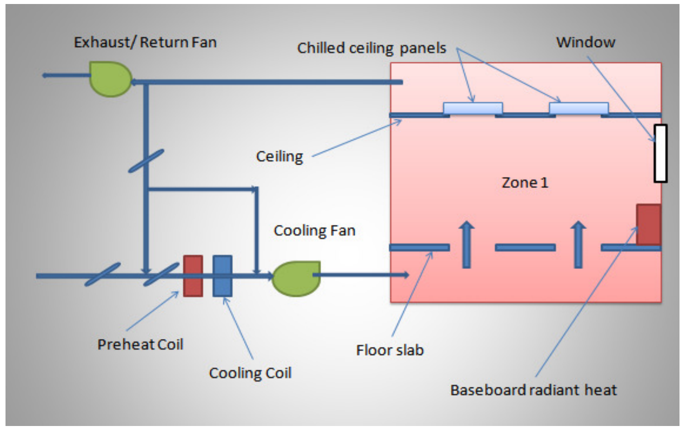


Figure 4.22: Displacement Ventilation w/Chilled Ceilings

### 4.2.18. Displacement Ventilation w/Passive Chilled Beams

In cooling mode, supply air will be introduce to the room with a higher temperature (usually around 63F instead of normally 55 F in regular systems) and lower speed to prevent occupant discomfort. A modulating damper varies the amount of air introduced to the room based on the space temperature sensor. If still there is need for further cooling, passive chilled beams in the ceiling will pick up the rest of the load. A return air bypass arrangement helps to provide dehumidification without the need for reheat.

The sources of mechanical energy consumption in cooling season in this type of systems are supply fan motor input power, return fan motor input power, electric preheat coil (if it is used for freeze protection instead of hot water coil) in air handling unit and electric baseboard reheat (if it is used for dehumidification instead of hot water coil). Duct air leakage, heat transfer from ducts, and efficiency loss in water coils are other sources that can indirectly increase the energy consumption of the system. Minor energy is consumed by low voltage power provided for control valves and dampers, and the power input to the variable frequency drives for supply and return fans that can be factored in supply and return fan consumption itself are the other sources of energy consumption.

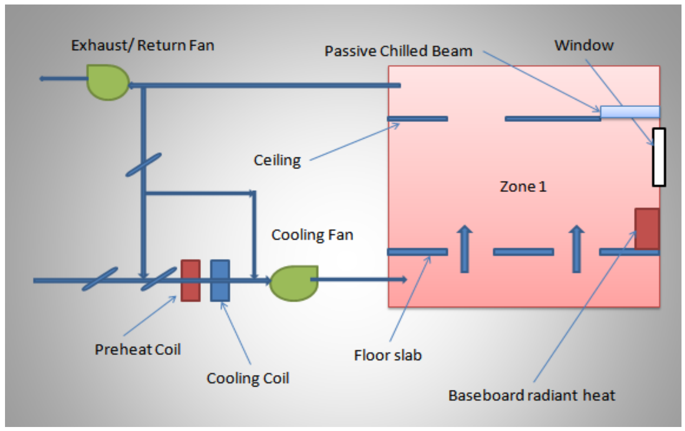


Figure 4.23: Displacement Ventilation w/Passive Chilled Beams

### 4.2.19. Active Chilled Beams

Chilled beam systems are primarily used for cooling and ventilating spaces, where indoor environmental quality and individual space control are appreciated. Chilled beam systems are dedicated outdoor air systems to be applied primarily in spaces where internal humidity loads are moderate. Active chilled beams are connected to both the ventilation supply air ductwork, and the chilled water system. The main air-handling unit supplies primary air into the various rooms through the chilled beam. Primary air supply induces room air to be re-circulated through the heat exchanger of the chilled beam. In order to cool or heat the room either cold (14-18 C) or warm (30-45 C) water is cycled through the heat exchanger. Re-circulated room air and the primary air are mixed prior to diffusion in the space. Room temperature is controlled by the water flow rate through the heat exchanger. (Virta et al. 2003)

In the cooling mode, the central air handling unit delivers the primary air that as it passes through nozzles of the active chilled beam that is installed at ceiling, causes the induction of the room air into the beam and mixes two streams of the air together, and then goes over an auxiliary cooling coil (only if the main cooling is not sufficient) in the passive chilled beam and then enters the room to offset the room sensible load.
If there is no primary air from the main air handling unit no induction will occur, and therefore the active chilled beam operates similar to a passive chilled beam.
The chilled beam system provides excellent thermal comfort, energy conservation and efficient use of space due to high heat capacity of water used as heat transfer medium. (Virta et al. 2003)

The sources of mechanical energy consumption in cooling season in this type of systems are supply fan motor input power, return fan motor input power (if it is required), electric preheat coil (if it is used for freeze protection instead of hot water coil) in air handling unit and electric baseboard reheat (if it is used for dehumidification instead of hot water coil). Duct air leakage, heat transfer from ducts, and efficiency loss in water coils are other sources that can indirectly increase the energy consumption of the system. Minor energy is consumed by low voltage power provided for control valves and dampers, and the power input to the variable frequency drives for supply and return fans that can be factored in supply and return fan consumption itself are the other sources of energy consumption.

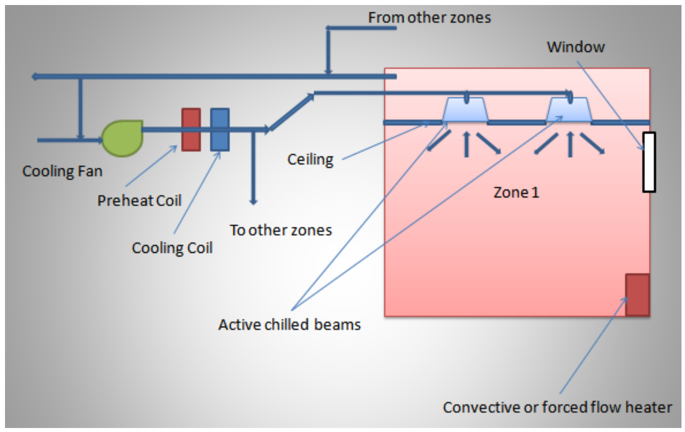


Figure 4.24: Active Chilled Beams

### 4.2.20. Passive Chilled Beams

Passive chilled beams comprise a heat exchanger for cooling, and when desired for heating. The operation is based on natural convection. The primary air is supplied to the space using separate diffusers either in the ceiling or wall, or alternatively through the raised floor. (Virta et al. 2003)

Passive beams are basically chilled water coils at the ceiling level, which through natural convection cool the room.

In cooling mode natural ventilation moves the hotter air up near the ceiling, air becomes cold and heavy and drops down to the room lower levels to provide sensible cooling. In these systems a supplementary air conditioning system provides all the required latent cooling, some sensible cooling and also provides needed cold ventilation air. Auxiliary cooling only activates when the main cooling cannot provide the sufficient sensible cooling.

The chilled beam system provides excellent thermal comfort, energy conservation and efficient use of space due to high heat capacity of water used as heat transfer medium (Virta et al. 2003).

The sources of mechanical energy consumption in cooling season in this type of systems are supply fan motor input power, return fan motor input power, electric preheat coil (if it is used for freeze protection instead of hot water coil) in air handling unit and electric baseboard reheat (if it is used for dehumidification instead of hot water coil). Duct air leakage, heat transfer from ducts, and efficiency loss in water coils are other sources that can indirectly increase the energy consumption of the system. Minor energy is consumed by low voltage power provided for control valves and dampers, and the power input to the variable frequency drives for supply and return fans that can be factored in supply and return fan consumption itself are the other sources of energy consumption.

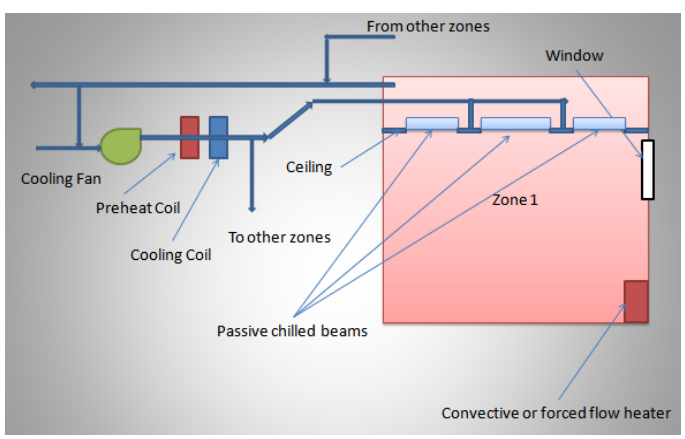


Figure 4.25: Passive Chilled Beams

### 4.3. Summary

In this chapter we have presented a brief description of some of the most popular cooling systems available for commercial use in the building industry. After reviewing the range of possible cooling systems in this chapter, the following chapters focus on the main energy consumer components which are common in these systems, such as supply fan, return/exhaust fan, chiller, compressor, condenser fan, cooling tower fan, chilled water pump, condenser water pump, fan coil unit fan, and terminal unit fan.  All systems can be broken down into a number of these components. The inefficiency in heat transfer in the cooling coil and quantity of air leakage from the ducts also contributes to increases in required energy consumption in some of these elements. These are the components that we use in a platform for system ECaE calculations, where only some minor adjustment are required to analyze every system. This is further explained in the next chapters.

# CHAPTER 5

# SETTING UP THE RISK ANALYSIS STRUCTURE

## 5.1. Risk Fundamentals

By understanding risk, measuring it and weighing its consequences, risk-taking has been converted into one of the prime catalysts that drives modern Western society. (Aven T., 2003)

There should be no doubt that risk and uncertainty are important concepts to address as part of our decision-making in many situations. The challenge is to know how to describe, measure, and communicate risk and uncertainty (Aven T., 2003). An old Greek belief was that the worst thing that could happen to a person is to make judgment and act upon his judgment without enough considerations and proper debating about the consequences (possible risks) of his judgment and action. Ever since and throughout the history of mankind, understanding of the risk and methods of quantifying it has been subject of many debates, articles and books, and importance of including risk analysis in different fields have been discussed as an important base for scientific decision making.

Terje Aven (2003) lays out a solid framework for planning, conducting and using risk analysis. To construct the basis of the risk analysis in this research we have followed this book's recommendations.

The basic elements of a risk analysis (Aven T., 2003) are as follows: A risk analyst (or a risk analyst team) conducts a risk analysis. Focus is on the future performance of the system (the world), and in particular on some observable quantities reflecting the performance of the system, $Y$ and $\mathbf{X} = (X1, X2, \ldots, Xn)$. Based on the analyst's understanding of the world, the analyst develops a model (or several models) that relates the overall system performance measure $Y$ to $\mathbf{X}$, which is a vector of quantities, on a more detailed level. The analyst assesses uncertainties of $\mathbf{X}$, which could necessitate simplifications in the assessments, for example using independence between the quantities $Xi$. Using probability calculus, the uncertainty assessments of $\mathbf{X}$, together with the model, give the results of the analysis, i.e. the probability distribution of $Y$, and a prediction of $Y$. The uncertainty distribution of $Y$ and $\mathbf{X}$**,** are known as predictive distributions.

Therefore the book recommends choosing only quantities that can express the real world and calls them observable quantities. In other word based on the book's presented methodology observable quantities are the group of factors that originally and at the time of the analysis are not known, but have the potential of becoming known, if the system under analysis actually become implemented in the real world. The book emphasizes that the value of an observable quantity should be very well defined and conventions and procedures should be available for expressing how to measure it, and no ambiguity should be presented in doing so. Thus an observable quantity should have a true and objective value and therefore when the system is actually implemented, these factors will have real values that can be assigned to them. In this thesis we have followed Aven's guidance in selecting the observable quantities for our model. Observable quantities here are individual equipment performances, total equipment capacity based on either system airflow or required cooling, first year ECaE and average five years energy consumption. Coil performance, system air leakage and calculated cooling load accuracy are the other observable quantities.

Terje Aven (2003) emphasizes the need to predict the observable quantities, and assigning probability distributions to each of them. There are several approaches that can be used to specify the probability distribution: (1) derivation of an assigned distribution based on classical statistics; ( This method can be used when the analyst decides that the available data is sufficient and relevant for the uncertainty assessment of the output, and the number of observations is large enough ); (2) analyst judgment using all sources of information; (This method can be used when data are not available or are only partially relevant to the analyzed output; the analyst is in charge of gathering, summarizing, rationalizing the available knowledge and developing applicable probability distributions, and (3) formal expert elicitation; ( this method should be based on structured input from a few individuals acknowledged as experts in the field ).

Terje Aven (2003) does not recommend a procedure of thinking through the underlying physical phenomena in order to produce some 'true' distributions for the observable quantities, and as a substitute the author recommends choosing a starting point for the analysis. If there is a lack of knowledge about observable quantities, he suggests just to use probabilities in order to express this lack of knowledge. By following his guidelines, our choice of probability distribution for all the observable quantities has been normal distribution, since normal distribution has been named the most useful distribution for this type of analysis in literature.

In this thesis the probability assignments to the observable quantities have been done based on both background information and expert judgment factors. The basis for the maximum allowable test tolerances set by the testing agencies are the basis for the setting up the maximum and minimum limits of the equipment performance levels. This means that lower and upper limits of the probability distribution for the equipment performances have been selected based on the values presented by the testing agencies as shown in (Table 5.1 below ).

Table 5.1: Individual components probability distribution

| **Equipment** | **Standard** | **Maximum Allowable Tolerance** |
|---|---|---|
| Chiller | ARI-550/590; 2003 | (+5%) full load, (+7.5%) part load |
| Compressor | ARI-550/590; 2003 | (+5%) full load, (+7.5%) part load |
| Fan | ARI-430; 2008 | (+7.5%) |
| Cooling Tower | Assumption | (+5%) |
| Pump | HI (Pump; paragraph 1.6.5.3. level A) | (+5%) |
| Terminal Unit | ARI-880; 2011 | (+5%) |
| Fan Coil Unit | ARI-440; 2008 | (+5%) |
| Air Leakage | Assumption | (+5%) |
| Coil | ARI-410; 2001 | (+5%) |
| Load | Assumption | (+_8%) |
| Equipment yearly efficiency degradation | Assumption based on industry manufacturers input | (+2%) |

Due to lack of available data for the probability distribution of the performance curves of the equipment, i.e. between the base and maximum allowable tolerance curves after equipment installation, it was decided to, consult with manufacturer's agents and experienced engineers and other experts in the HVAC field. With their help the selection of the uncertainty distribution for the HVAC equipment was done based on the following logics reasoning and assumptions.

1. Testing agencies typically present allowable tolerances in the form of +_5%, or +_7.5%, etc. But when the manufacturer's testing results show that the performance of an equipment is below the base line (i.e. between base line and the minimum allowed percent, (e.g. between 0 & -5%)), then the manufacturer automatically will not pursue the certification of his equipment for the original rating anymore, and instead he will certify that machine as an equipment with higher nameplate capacity. Therefore there will be no distribution occurrences of the performance curve in this "higher than average" region. An example makes this statement more clear. Assume a manufacturer is manufacturing a1000 tons, 0.6 KW/ton chiller. This means that the chiller at full load needs 600 KW to produce 1000 tons of cooling. Based on the testing agency +_5% allowance at full load (here we only discuss the full load condition, but the discussion should be extended for the part load condition also) this chiller can be certified for this category if the results of the test shows that (at full load) there is a need for between 570 to 630 KW to generate 1000 tons of cooling from this chiller. Obviously after testing the chiller on the manufacturing site the required power input falls either between 570 and 600 KW, or

between 600 and 630 KW, since any result outside of this margin means (on the higher side) the chiller has failed the test, and needs to be re-engineered and improved.
If we deal with case 1, let's assume the test results show that the chiller only needs 570 KW to produce 1000 tons of cooling (0.57 KW/ton efficiency). In this occurs it is most likely that the manufacturer shifts his chiller base curve from the original curve to this location and then builds the maximum (570*1.05=598.5 KW) and minimum allowable test tolerances around this new base curve. Therefore he will certify the same chiller not only for a slightly better efficiency (598.5/1050) or 0.57 KW/ton, but also for a higher capacity (1000*1.05=1050 tons) as well. Therefore for our simulations we eliminated a distribution possibility in this area. This means de facto that the uncertainty in the performance curves are only considering the second case, i.e. when the components underperform the base line.

2. The closer the final manufactured unit performance curve is to the maximum allowable test tolerance curve, the manufactured unit will cost less for the manufacturer to produce, and therefore manufacturers are biased towards clustering their equipment performance curved near the maximum allowable test tolerance curve.
Therefore we generated three sets of distributions between the base (0% deviation) and maximum deviation. The sets differ in the mean value of the deviation in equipment tolerances, i.e. we use 75%, 50% and 25% of the distance between the base curve and the maximum allowable deviation from the base. Standard deviation of 68%, 38% and 5% were assigned to each of these mean values, and the results of the three set of simulations were combined with a 0.1, 0.3 and 0.6 factor (in respective order) to produce equivalent

of a skewed probability distribution between the base line and the maximum allowable deviation with the mean value of the combined distribution located somewhere close to 75% of the distance between the base curves and the maximum allowable deviation curves. See figure 5.1.

The Monte Carlo simulation is done with each set producing energy consumption for the first year, energy consumption after 5 years and energy efficiency for the first year.

The three sets of simulations based on normal distributions around the three mean values was done to inspect the Monte Carlo results for each set as input to a discussion allowable test tolerance reduction recommendation.

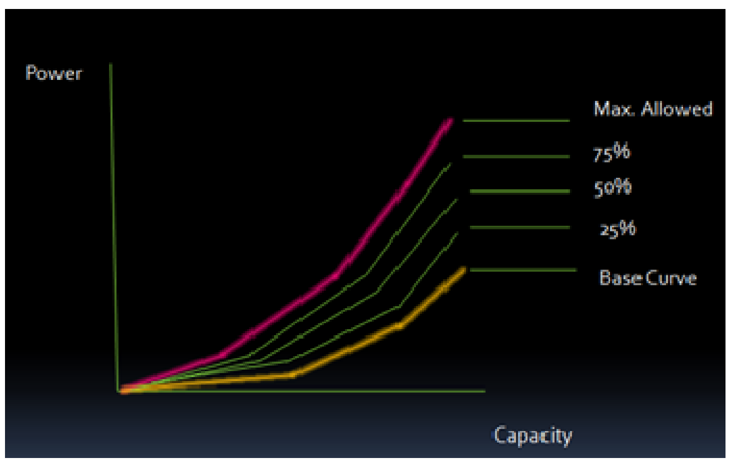


Figure 5.1: Performance curve selection

It is obvious distribution1 will result in a higher inefficiency because the likelihood of equipment being close to maximum deviation is highest, while set 3 will result in the lowest mean equipment is more likely to be closer to the baseline (nameplate) information. Distribution 2 will perform somewhere between these two. The results from each distribution (composed of a weighted average of the three distributions (with weighting factor of 0.1, 0.3 and 0.6) have been used in the analysis reported in later chapters.

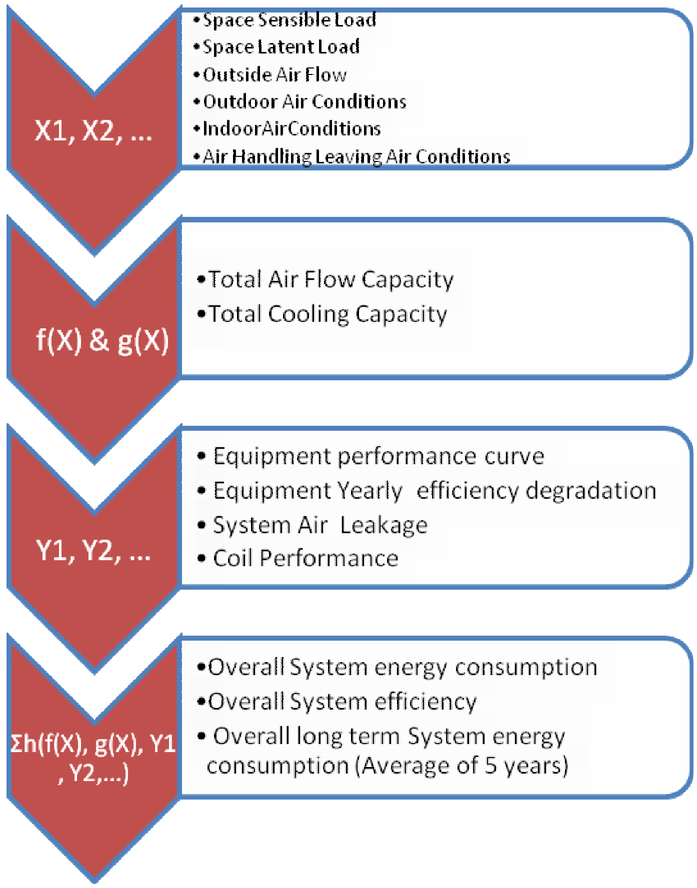


Figure 5.2: Platform structure

Our model produces observable quantities of system overall energy consumption, system overall efficiency and system long-term overall energy consumption (5 years average). They are functions of multiple other observable quantities as shown in figure 5.2 where all inputs have been assigned their own probability distribution as discussed above. The model outcomes provide insight into the overall system performance and through a sensitivity analysis enable the identification of risk contributors and inspect the effect of changes.

## 5.2. Development of the simulation Platform

### 5.2.1. Platform for Office building cooling system

Since current commercial simulation programs are not capable of directly analyzing the effects of equipment test tolerance in their algorithms a procedure (platform) capable of performing this task was needed to be developed. For this purpose a dedicated platform was developed in Microsoft Excel. It is not only capable of hourly deterministic simulation of the ECaE of the building cooling system, but also offers the opportunity to including the effects of equipment uncertainty in addition to other factors into the calculations.

This HVAC system calculation platform is composed of different sections. In section one (deterministic calculations), the platform receives the building demand side (calculated) inputs consisting of room sensible cooling load, room latent cooling load, quantity of outside air and the outdoor temperatures (dry and wet bulb) on an hourly basis. These inputs are calculated separately based on the building location, size, application, skin data, lighting schedules, etc.

These inputs are used in conjunction with the room and supply air conditions (dry and wet bulb temperatures, enthalpy and humidity ratio) to calculate the total air flow capacity and total cooling required for satisfying the cooling demand. In this section the selected cooling system for the application is broken up into its individual components, i.e. chiller, cooling tower, supply fan, etc. Then an acceptable performance curve is designated to each of these equipments. These curves show the variation of energy consumption of the equipment in (KW) versus part-load fraction, i.e. fraction of either maximum flow capacity (cfm) or fraction of maximum cooling (tons) generated by the equipment, expressed over the full range of the its capacity.

The deterministic calculations uses the baseline energy efficient performance curve for each equipment as specified in energy codes and standards (ASHRAE 90.1) to derive the overall energy consumption and energy efficiency of the cooling system. The results come in the form of a single value, such as 3000 KWh overall energy consumption or 1.4 KW/ton overall efficiency for a full day in the selected month (July). This value will later be used as a starting value for developing risk based expressions.

In the probabilistic section of the platform each component (equipment) is evaluated separately based on one or two acceptable performance curves, due to lack of certainty about which type of equipment is eventually purchased for the building.

The simulation may in fact provide more realistic results if more than two performance curves would be included in calculations to express the variability over the products from different manufacturers, but to simplify the procedure we used only one or two performance curves per equipment, and that has contributed to some camel-back distributions for some outputs.

We use the Trane Trace 700 program equipment library for the acceptable performance curves of different equipment. A formula was derived to generate the base performance curves, and the family of curves that represent deviations from the base performance were generated as well.

AHRI or ARI (Air Conditioning and Refrigeration Institute) is one of the largest trade agencies in United States, which represents more than 300 HVAC manufacturers within the industry, representing more than 90 percent of the residential and commercial air conditioning equipment manufactured and sold in North America. AHRI has a certification program that is relied heavily upon by regulators for accurate and unbiased evaluation of HVAC equipment. It develops industry-recognized performance standards for industry equipment. In this research we have utilized ARI standards for fans, coils, cooling tower fans, chillers, direct expansion units and water cooled unitary units.

The Hydraulic Institute (HI) is the largest association of pump industry manufacturers in North America. The Institute, created in 1917, has served member companies and pump users by offering a wide variety of programs including providing product standards and a forum for the exchange of have utilized HI standards for pumps.

A mechanism embedded in the Excel calculation allows that based on random sampling through integration with Model Center software and Monte Carlo performance curves for any of the equipments is selected. A selected performance curve represents the level of energy consumption and thereby the efficiency of a specific equipment. Combining the energy consumption or efficiency of all equipments that make up the whole system, leads to the overall ECaE.

Based on the input from industry experts an acceptable energy efficiency loss of 1 to 2 percent per year is a reasonable assumption for all the HVAC equipment. In our calculation another random function generates the ECaE for all the equipment based on five-year period efficiency degradation. The results from the average deterioration of efficiency in five years could be a more realistic way of presenting ECaE of a cooling system, instead of relying only on the results for the first year.

As it was said earlier the inputs to the platform from the demand side are hourly room (space) sensible cooling load (RSH), hourly room (space) latent cooling load (RLH) and hourly outside air quantity ($cfm_{oa}$). Outdoor condition is given in the design day weather scenario and therefore is fixed and is part of the input from the demand side also ($T_{oa, db}$ , $T_{oa, wb}$, $W_{oa}$). The uncertainty in the demand side is captured by adding +_8% to the demand side load. This accounts for load variability due to multiple sources, such as (1) the simplified calculation of the load in the platform, especially the ignorance of uncertainty in the behavior and use of the building, (2) the simplification of a monthly weather scenario in one design day. As we will explain later, both sources of uncertainty can be captured by sourcing simulated (rather than design day calculated) demand side information to the calculations.

For the ease of calculations we have made this assumption that there will be no air bypassed around the cooling coil, and therefore dehumidification air quantity ($cfm_{da}$) and supply air quantity ($cfm_{sa}$) are the same value, and equal to the total air that enters the space. The following basic formulas have been used to calculate the total supply air flow quantity ($cfm_{sa}$) and total required cooling (tons of refrigeration) on an hourly basis.

$cfm_{da} = cfm_{sa} = TSH/(1.08*(T_{edb} - T_{ldb})) = RSH/(1.08*( T_{rm} - T_{sa}))$ (eq. 5.1)

$OASH=1.08*cfm_{oa}*(T_{oa}- T_{rm})$ (eq. 5.2)

$OALH=0.68*cfm_{oa} *( W_{oa} - W_{rm})$ (eq. 5.3)

$TH=RSH+RLH+OASH+OALH$ (eq. 5.4)

Where RSH is room sensible load (Btu/h), OASH is outdoor air sensible load (Btu/h), OALH is outdoor air latent load (Btu/h), $cfm_{oa}$ is outdoor air flow capacity, $T_{oa\ is}$ outdoor air dry bulb temperature (Degree F), $T_{rm}$ is room dry bulb temperature (Degree F), $W_{oa}$ is outdoor humidity ratio (grains of moisture in pounds of dry air), $W_{rm}$ is room humidity ratio (grains of moisture in pounds of dry air), TH is total cooling required, RSH is room sensible load, and RLH is room latent load. (These formulas can be found in air conditioning literature or handbook, e.g. ASHRAE Fundamental Handbook)

The calculations are set up with the following provisions:

ARI-410 (2001 standard for forced-circulation air-cooling and air-heating coils) section 6.4.1, states that rating shall be such that any coil which is selected at random shall have a total capacity, when tested, not less than 95% of its published total capacity. Therefore the choices are to either accept an underperformance (by up to 5%) coil and uncomfortable space condition resulting from this underperformance, or oversize the coil by 5% to make sure the required cooling is always available. The second case is the usual choice selection of the design practitioners, therefore in our research we allowed (0 to 5%) increase for the total cooling required for the coil above the calculated cooling by the demand side.

ASHRAE 90.1 (2010) section 6.4.4.2.2, lays down the maximum allowable duct leak performance with the following formula:

$L_{max}=C_LP^{0.65}$ (eq. 5.5)

with $L_{max}$ as maximum permitted leakage presented by cfm/100 $ft^2$ of duct surface, and $C_L$ as a constant value (usually equal to 4) and P design duct pressure.

Since the actual duct lay out is not available, we included 0 to 5% duct leakage as acceptable industry-wide characteristics of most of the flow regimes in the HVAC field. The platform is equipped with randomized mechanisms that are able to include the effects of demand side uncertainties (+-8%) and the effects of coil capacity tolerance (0 to 5%) and air leakage from the ducts (0 to 5%) in the calculation of the total air flow and total cooling load. These probabilistic outcomes for total airflow and total cooling load then is used to determine the part load flow and part load cooling fraction which are the inputs to determine performance given an equipment performance curve in the hourly ECaE calculations.

### 5.2.2. Platform for Healthcare facility cooling system

Hospitals are extremely complex buildings with many unique requirements. Architects, designers, contractors, developers, owners, and lessees of large hospitals thus end to pay less attention to energy usage because they are so focused on meeting the hospital's numerous other requirements. (Bonnema et al.)

As in other types of buildings, health care facility HVAC systems are required to establish comfortable environmental conditions through the control of temperature, air movement, relative humidity, noise, and objectionable odors. Environmental control is important, not merely in providing personal comfort, but in facilitating the healing process: simply stated, a comfortable patient heals faster. (ASHRAE 2003)

A HVAC system designed for a healthcare facility should be responsible not only for providing comfort for the hospital occupants, it shall be also capable of providing a proper environment for other functions such as infection control, environmental control for specific medical functions, hazard control and building and people safety.

Health care professionals utilize a wide range of specialty equipment and engineering controls and observe rigid operational disciplines, practices, and techniques, to control infection. Infection control equipment and practices are regulated by federal and state government authorities, which also set standards for engineering controls. (ASHRAE 2003)

The HVAC system utilizes control functions including ventilation and contaminant exhaust or the process of lowering the concentration of airborne contaminants in a space by exhausting contaminated air and supplying the space with makeup air without contamination, directional airflow control by the establishment of a relative differential pressure between the spaces. (Directional airflow out of a space (positive relative pressurization) is utilized when there is a need to protect room occupants or materials from airborne contaminants outside the space. Airflow into a space (negative pressurization) is utilized when it is desired to prevent contaminants released in the space from spreading to adjoining areas), and high efficiency filtration. In many applications, all or most of these functions are performed simultaneously.

Factoring all the above requirements we can come to this conclusion that the main differences between healthcare facilities and office buildings are (1) maintaining relative pressure between spaces in healthcare facilities is very important (2) healthcare facilities have higher requirement for supply fan powers due to high efficiency filtration (e.g. HEPA filter requirement at air handling unit and supply diffusers).

The first item results in higher volume of outside air for pressurization of the building spaces, and the second item results in higher static pressure for supply fan and terminal units/ fan coil units to overcome.

The increased quantity of outside air is a part of the demand side inputs, but increases of static pressure and their effect on supply fan selection and use deserve special attention as part of calculating the supply fan and terminal unit/ fan coil unit performance.

ASHRAE 90.1 (2010), in Tables 6.5.3.1.1A and 6.5.3.1.1B offers a method for calculation of the effects of higher static pressure due to extra filtration on allowable fan power.

Based on ASHRAE 90.1 (2010) maximum allowable fan hp (horsepower) for a constant volume and a variable volume fan shall be smaller or equal to "cfm*0.0011" and "cfm*0.0015" respectively. When due to requirement of the specific application extra devices are required (e.g. extra filtration for healthcare facilities) then bhp (brake horsepower) of the constant volume and variable volume fans shall be smaller or equal to "cfm*0.000971+A" and "cfm*0.0013+A" respectively, where "A" is equal to sum of multiplication of all the extra devices pressure drops by air flow capacity (cfm) which is passing that device.  "A=sum of (PD*cfm/4131)". It is customary to increase the bhp value to the next immediate upper size to get the working hp value. In this work we make the assumption that calculated bhp is equivalent with the hp for the ease of the calculations.

The above considerations are used in the calculations of systems when applied in hospitals.

# CHAPTER 6

# SIMULATION RESULTS

## 6.1. Simulation goals

This chapter explains the systematic approach of developing expressions of risk and reliability in order to increase the performance risk knowledge related to the commercial cooling systems. (See Figure 6.1 below)

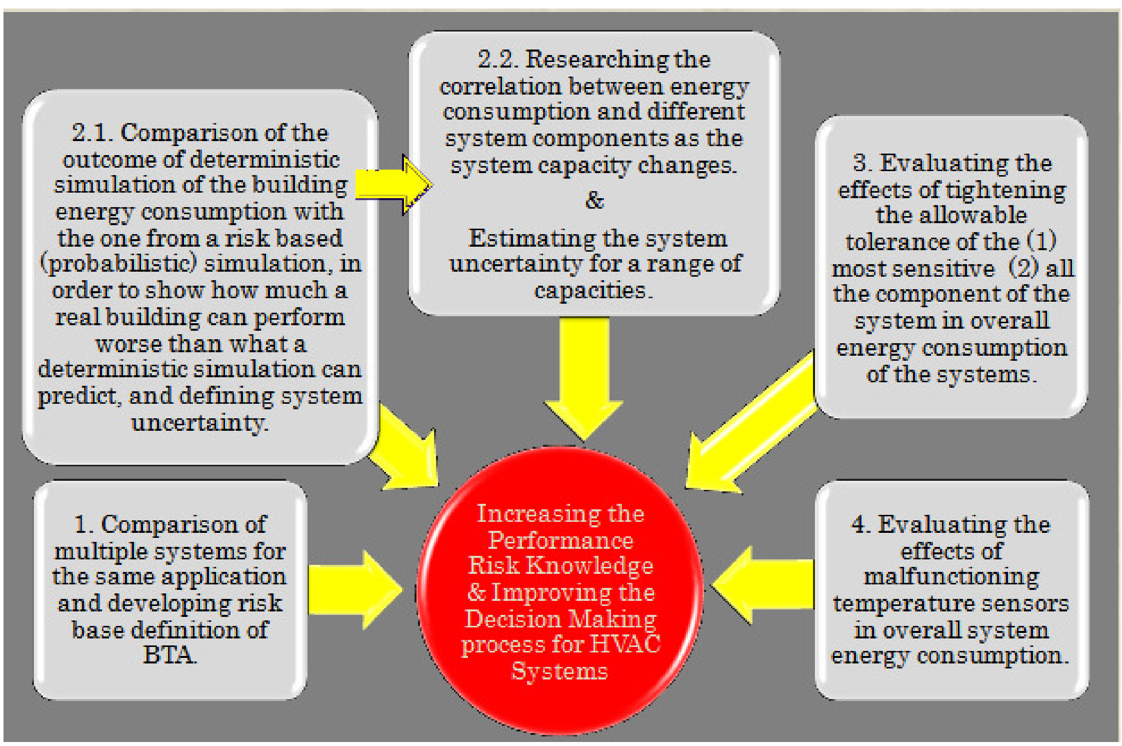


Figure 6.1: Overview of the targeted plan

In order to develop the desired risk expressions, we selected the six most popular systems to provide cooling for office buildings and healthcare facilities and performed multiple Monte Carlo simulations for each system in order to calculate the energy consumption of the system in a detail hourly form.

We plan to calculate the statistical average of the energy consumption of the systems and establish that as the basis for identifying risk relative to that average value based on the “better than average” or BTA. For each system all the energy consumption values less than this average and the bin size registered for them represent the chances of that specific system to perform better than average and all the energy consumption values more than this average and the bin size ( percentage of occurrence of result in a certain value range ) registered for them represent the chances of that specific system to perform worse than average. The expression of risk in these conditions would be  such as "there is x% (percent of registered bin to total bin size) chance that system "A" performs y% (percent difference between the registered consumption to the average consumption) better than average" and "there is z% chance that system "A" performs w% worse than average".

Also by performing the simulations and analyses in this chapter we will show:

1. As the system capacity size changes, the most influential parameters on the uncertainty of the system changes as well. We will define a normalized value for the outcome of the simulation that can express and can be used as the percentage of uncertainty for each system.

2. The current energy efficiency evaluation can be improved by using risk based analysis. We will show that by using this method for a mid size office building or healthcare facility there will be x% chance of up to y% energy savings.

3. We will show that using sensitivity analysis can provide insight to the operation of the systems that then can help to improve the energy efficiency and consumption of the system. We will show for a mid-size office building and healthcare facility this energy consumption saving could be as high as z%.

4. We will also show that when improving the system based on the results of the sensitivity analysis, there is up to u% chance that the peak energy consumption of the original system is up to v% higher than the maximum energy consumption of the improved system. This could be a crucial cost issue, since most of the utility providers, set the base charging price of the electricity for a building based on the maximum usage (peak) of the electricity.

5. We also will show that encouraging the testing standard agencies to decrease the allowable test tolerance for the equipment from the current standards can translate to lower energy consumption of the different systems serving the same application by as much as t% .

## 6.2. System Selection

A literature review along with an expert elaboration showed that the following six systems are the most suitable and also commonly utilized systems among the design practitioners for both office buildings and healthcare facilities. Variable volume air, with water cooled chillers; variable volume air, with air cooled chillers, Package unitary roof top unit, Water cooled unitary air conditioning unit, Fan coil system with water cooled chillers, and fan coil units with air cooled chillers, are the six selected systems that throughout this research we will refer to them as system 1 through 6 in the same order. It should be said that the last two systems have a higher percentage of popularity overseas, specifically in countries at Eastern Asia. Of course in some parts of healthcare facilities such as operating rooms, it is common to use all constant volume air handling units, but these parts making only 5-6% of the whole facility occupied foot-print. Therefore we have based our research on analyzing the effects of equipment test tolerance on these six systems for typical medium size office building and healthcare facility as the building is completely served by a single system type. ASHRAE 90.1, 2010, in section 6.5.2., prohibits reheating the air after cooling it first, unless under some specific conditions. Therefore to avoid simultaneous cooling and heating, we will not include any reheat in terminal units in our calculations in this research.

### 6.2.1. System 1: Variable air volume system, with water cooled chillers

The main energy consuming components of this system are supply fan, return fan, terminal units fans, water cooled chiller, cooling tower fan, chilled water pump and condenser water pump. Performance curves for each of these seven main components have been selected from the library of Trane Trace 700 software which are two different performance curves for water cooled centrifugal chillers, two different performance curves for supply fans, two different performance curves for return fans, two different variable frequency type performance curves for cooling tower fans, one performance curve for terminal unit, one performance curve for chilled water pump and one performance curve for condenser water pump. It should be said that using more than one performance curve for some of these equipments contribute to the unusual camel-back distribution shape of the uncertainty results, instead of usually expected bell-shape distributions. In each case family of the performance curves based on gradual increase of 0.5 or 1% tolerance from the curve default value up to the maximum allowable test tolerance based on ARI and HI standards have been generated. (See Figures 6.2, 6.3, 6.4 and 6.5 for sample of these generated performance curves.)

The lowest curve (default curve) is used to run the deterministic calculations, while the family of the curves (the default curve along with the curves generated by off-setting the default curve) has been used for probabilistic calculations.

Other influential factors on the energy consumption of this system are the test tolerance allowance for cooling coil (cooling coil performance) and amount of air leakage from the ductwork. Of course the effects of cooling load calculations accuracy is another major factor in final energy consumption of the system, which has been assumed as +_8% for all the calculations. See discussion in chapter 1, around the work of Munoz (Dominguez-Munoz et al. 2010) regarding this assumption.

The peak load condition of the equipment for the default curve on both deterministic and probabilistic calculations has been derived from the acceptable maximum equipment power consumption from ASHRAE 90.1. (See Table 6.1, below)

Table 6.1: System 1 component efficiency@ full load condition

| Component | Efficiency @ full load | Reference |
|---|---|---|
| Variable Volume Fan | hp = cfm * 0.0015 | ASHRAE 90.1 2010, Table 6.5.3.1.1A |
| Constant Volume Fan (Terminal Units) | hp = cfm* 0.0011 | ASHRAE 90.1 2010, Table 6.5.3.1.1A |
| Water Cooled Chiller (Centrifugal Compressor) | 0.634 kw/tons | ASHRAE 90.1 2010, Table 6.8.1C |
| Cooling Tower Fan | 20 gpm/hp | ASHRAE 90.1 2010, Table 6.8.1G |
| Chilled Water Pump | 22 Watts/ gpm | ASHRAE 90.1 2010, Section G3.1.3.10 |
| Condenser Water Pump | 19 Watts/ gpm | ASHRAE 90.1 2010, Section G3.1.3.11 |

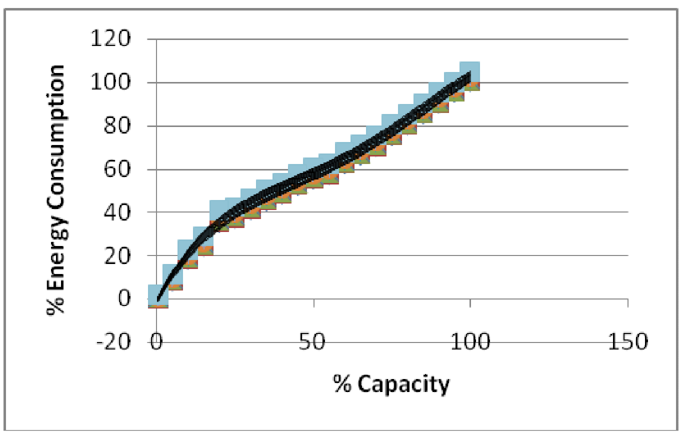


Figure 6.2: Centrifugal Chiller performance curves - System 1

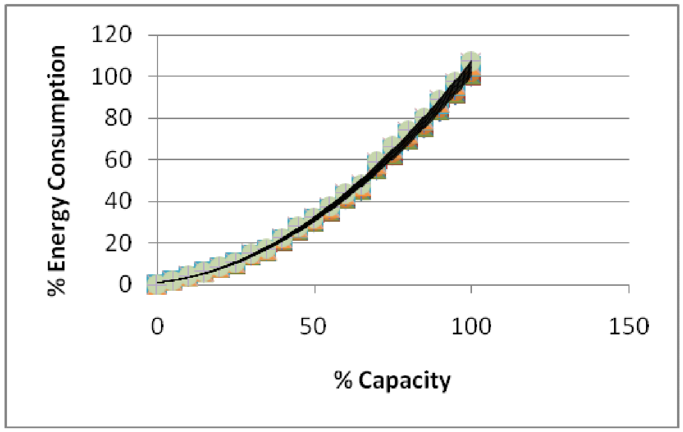


Figure 6.3: Supply and Return Fan performance curves – System 1

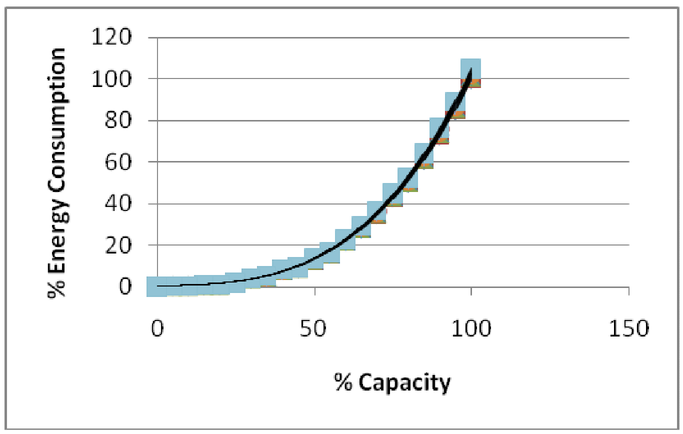


Figure 6.4: Cooling Tower Fan performance curves – System 1

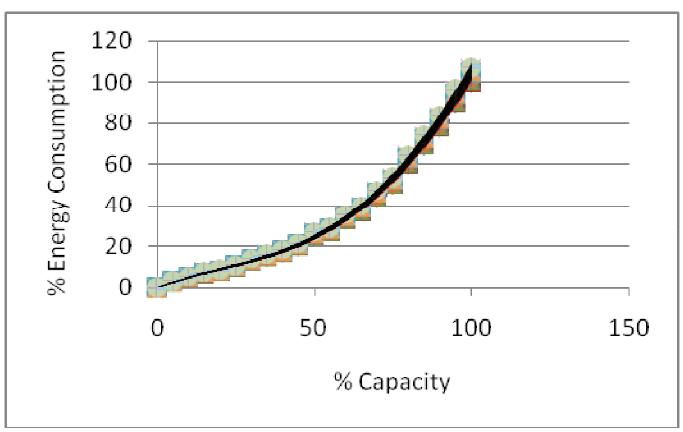


Figure 6.5: Chilled water and Condenser Water Pump performance curves – System 1

Since there is no available manufacturer's record data that shows the exact location of the real performance curves of the equipments, three sets of Monte Carlo simulations were performed with (1) location of the mean value of the energy consumption for all the equipments set at 25% of the consumption between default and maximum allowable tolerance higher than default value (2) location of the mean value of the energy consumption for all the equipments set at 50% of the consumption between default and maximum allowable tolerance higher than default value (3) location of the mean value of the energy consumption for all the equipments set at 75% of the consumption between default and maximum allowable tolerance higher than default value. Outputs of each simulation were energy consumption in first year, average energy consumption of 5 years and energy efficiency in first year.

In this case based on an analyst judgment and manufacturer's representatives input we decided that since the closer these percentages are to 0, it demands higher quality construction and therefore higher expenses for the manufacturers, a weighted assumption should be done to have a distribution that reflects the reality. We assigned 60% to simulation with Mean of 75% (closest to the upper limit allowed), 30% to simulation with Mean of 50% and 10% to simulation with Mean of 25% (closest to default value).

An average distribution for the first and five years average distributions were generated as well. Followings are the output distributions from Monte Carlo simulation for system 1. Also in each case a sensitivity analysis has been performed to show the degree of influence of different component in each case. (Calculations are done for a typical day in the month of July for the US climate zone 3 (ASHRAE 90.1)).

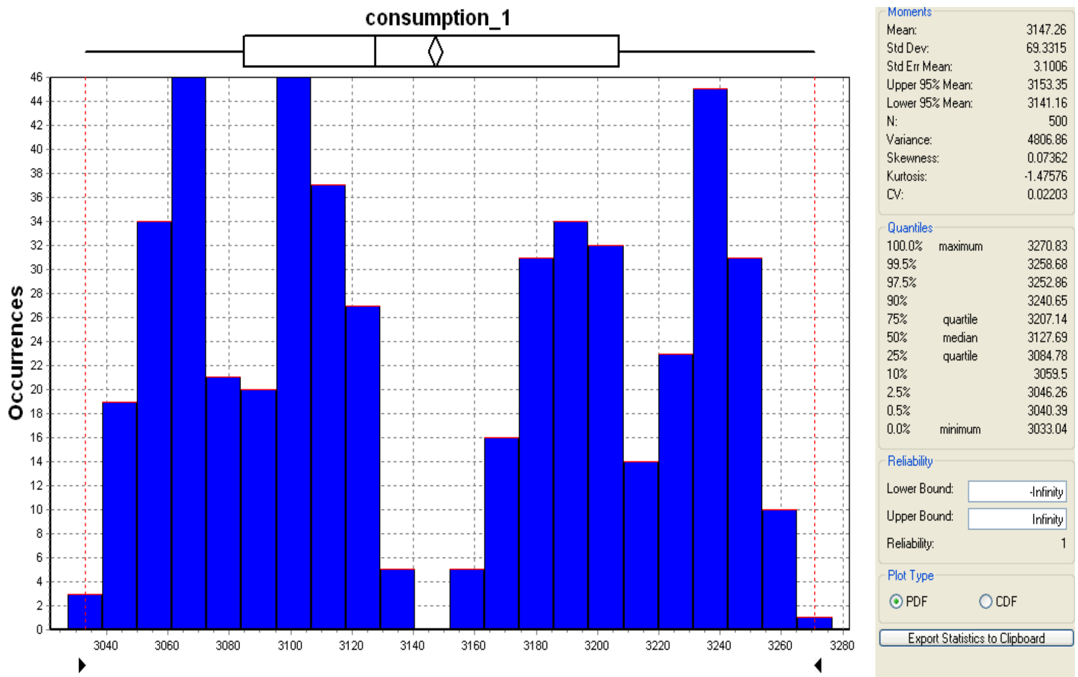


Figure 6.6: Distribution of Energy consumption for the first year– System 1 (Mean value @ 75%)

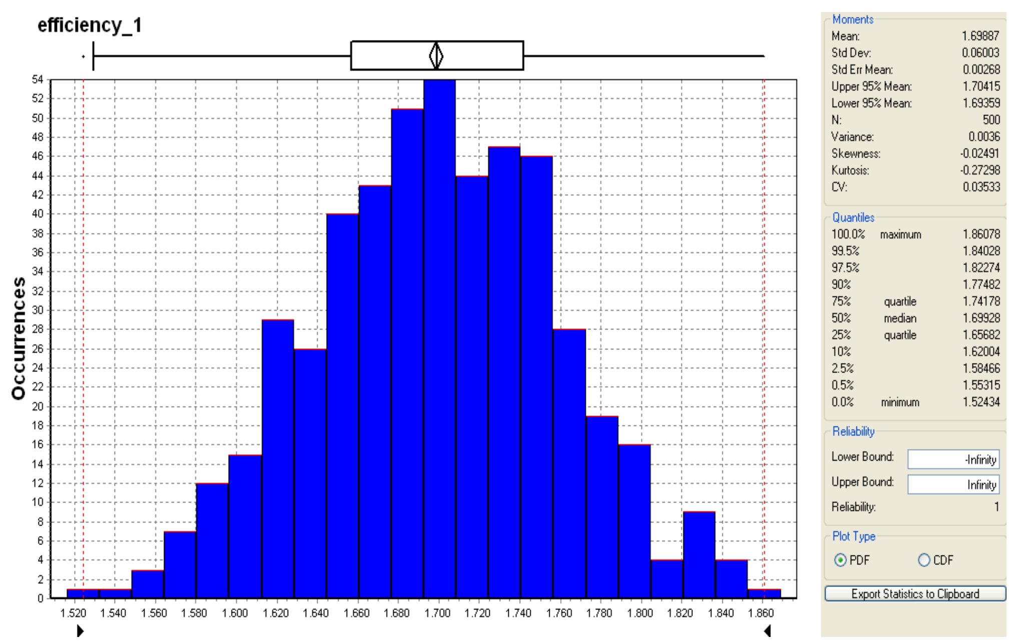


Figure 6.7: Distribution of Energy efficiency for the first year– System 1 (Mean value @ 75%)

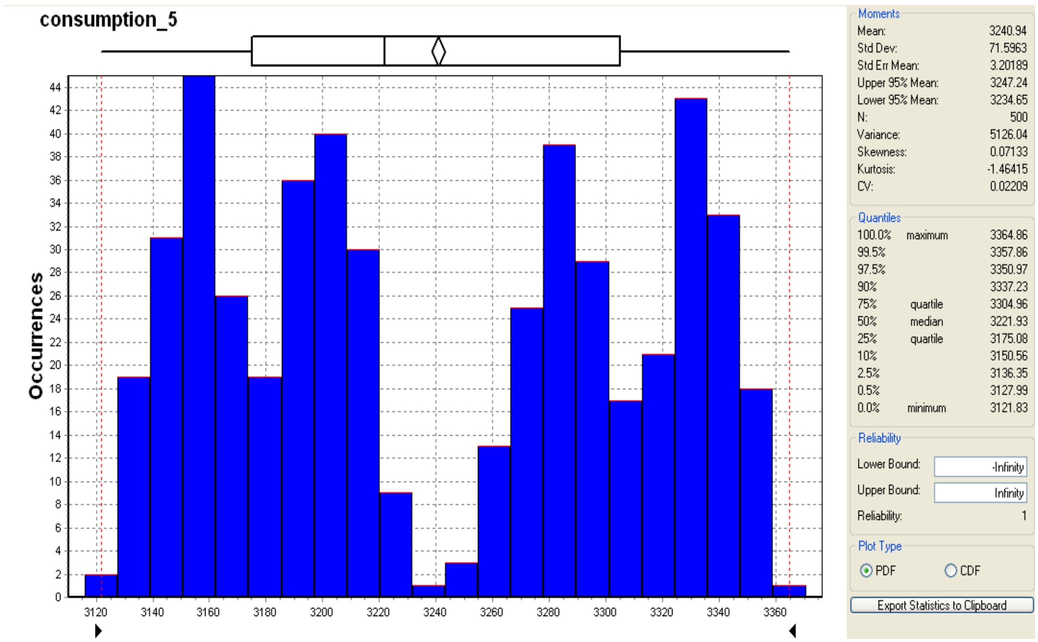


Figure 6.8: Distribution of Energy consumption for average 5 years– System 1 (Mean value @ 75%)

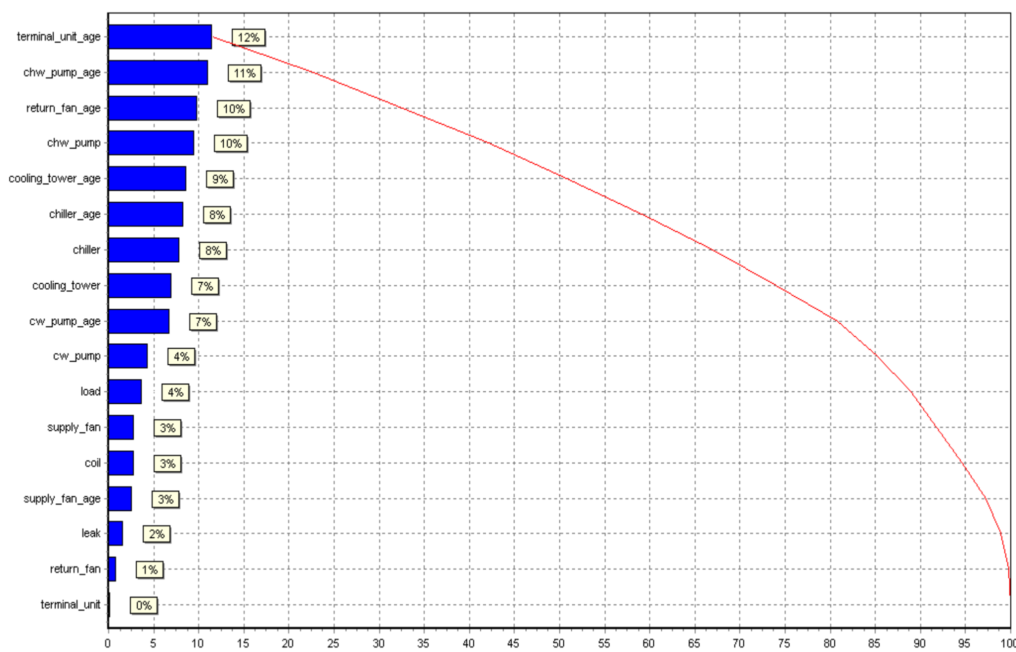


Figure 6.9: Sensitivity analysis results for System 1 (Mean value @ 75%)

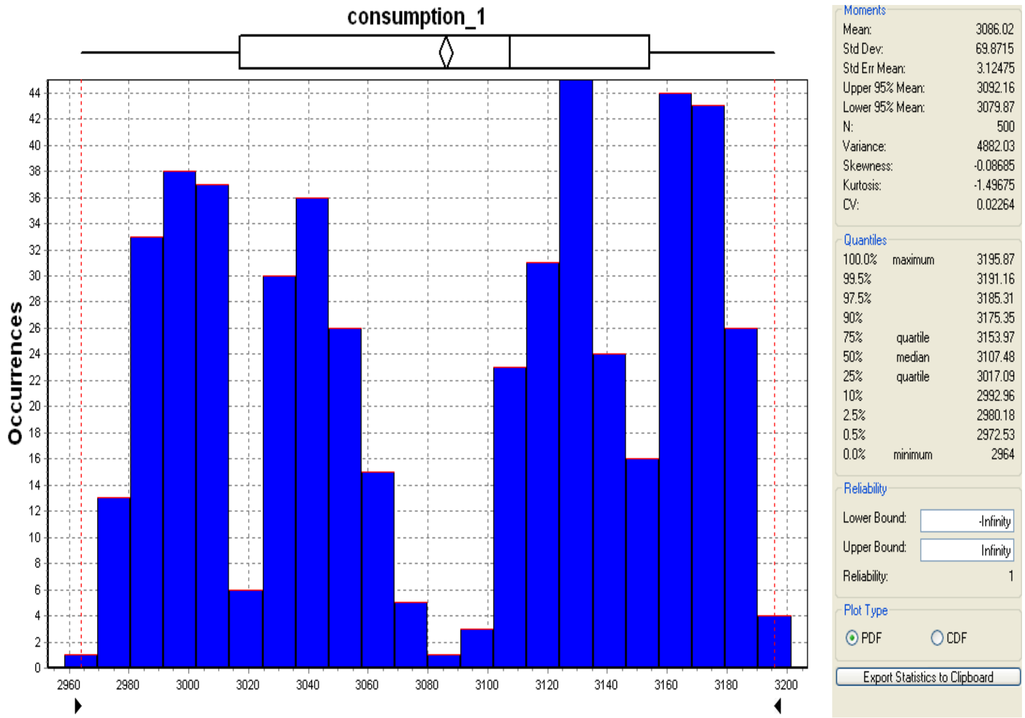


Figure 6.10: Distribution of Energy consumption for the first year– System 1 (Mean value @ 50%)

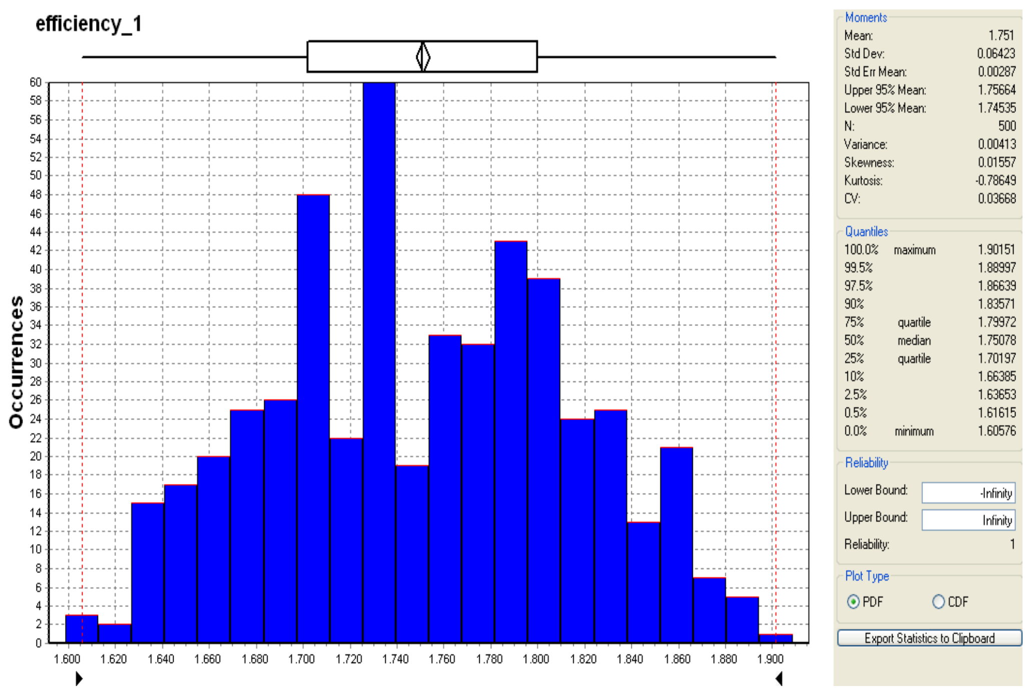


Figure 6.11: Distribution of Energy efficiency for the first year– System 1 (Mean value @ 50%)

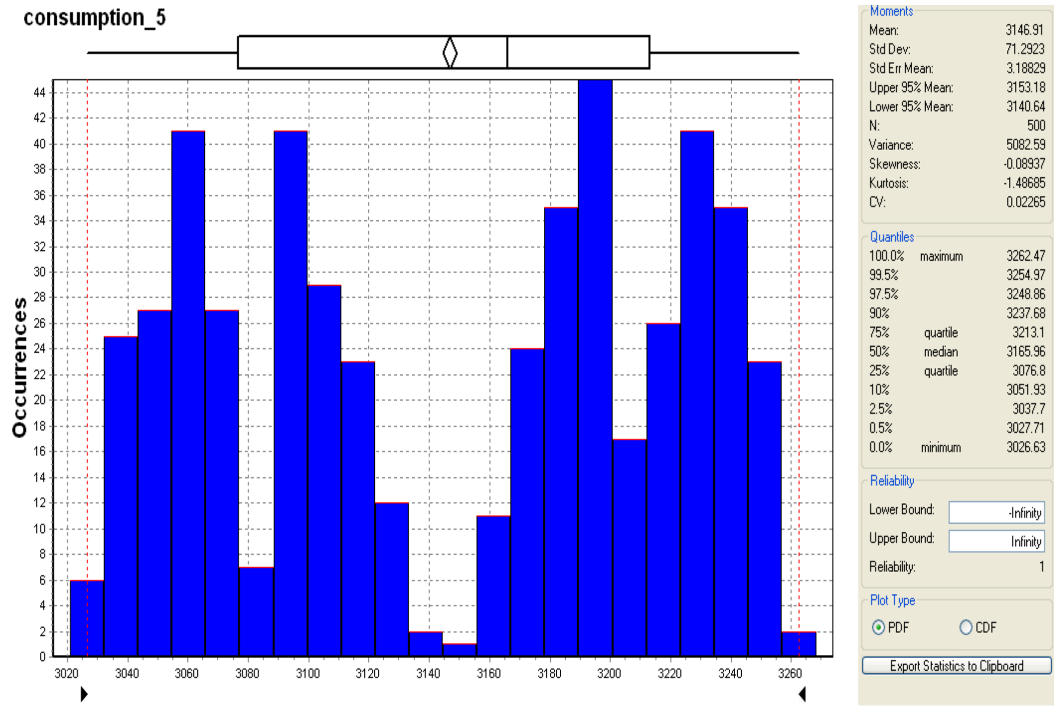


Figure 6.12: Distribution of Energy consumption for average 5 years– System 1 (Mean value @ 50%)

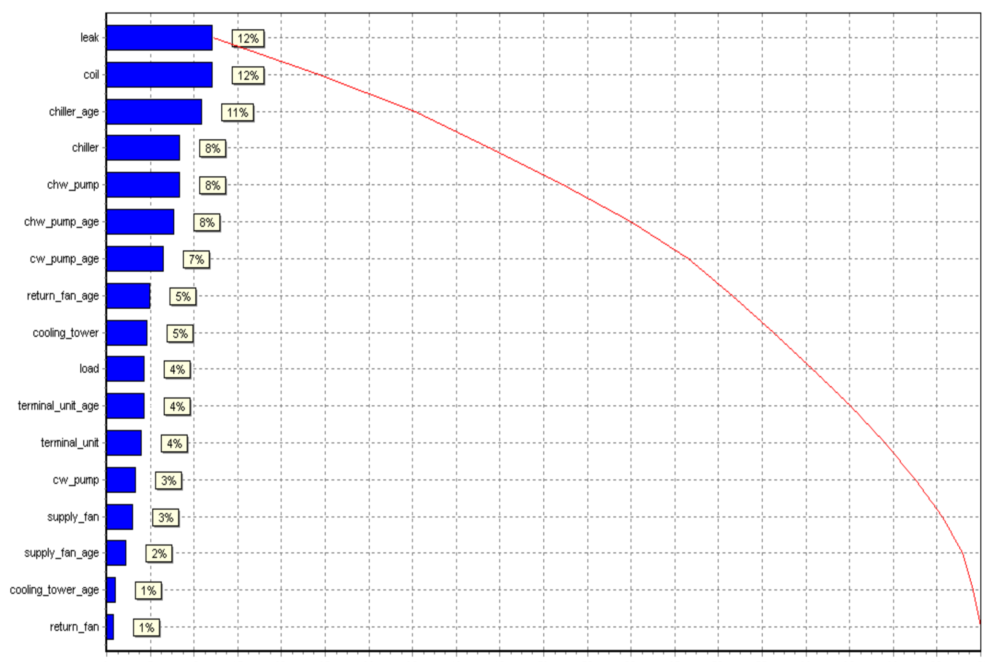


Figure 6.13: Sensitivity analysis results– System 1 (Mean value @ 50%)

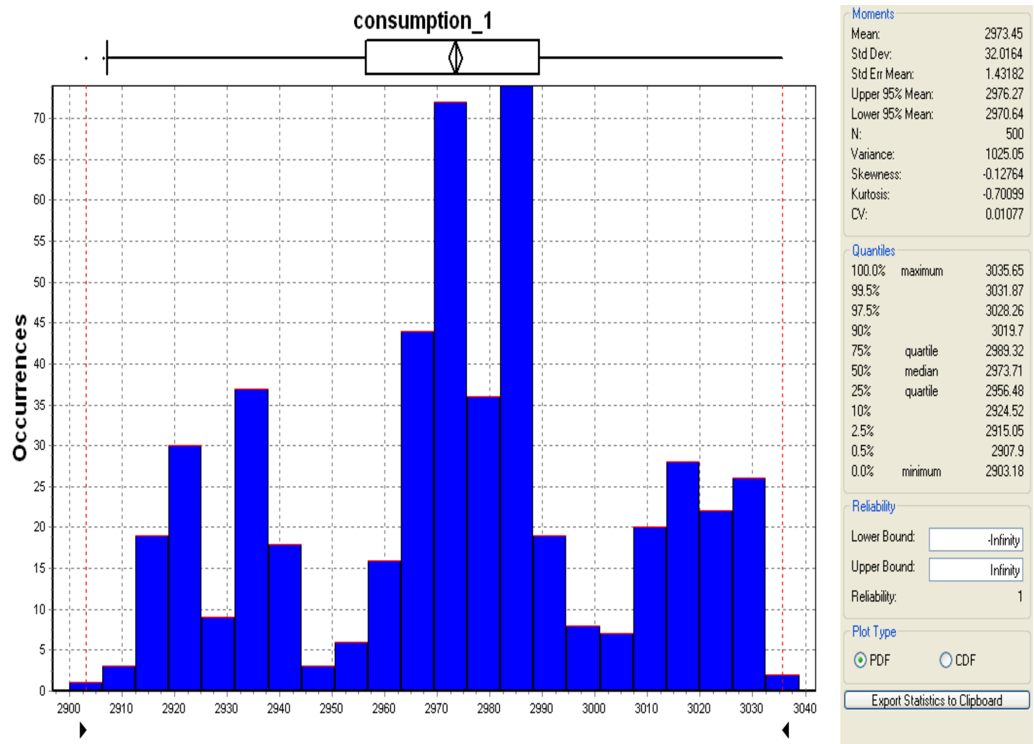


Figure 6.14: Distribution of Energy consumption for the first year– System 1 (Mean value @ 25%)

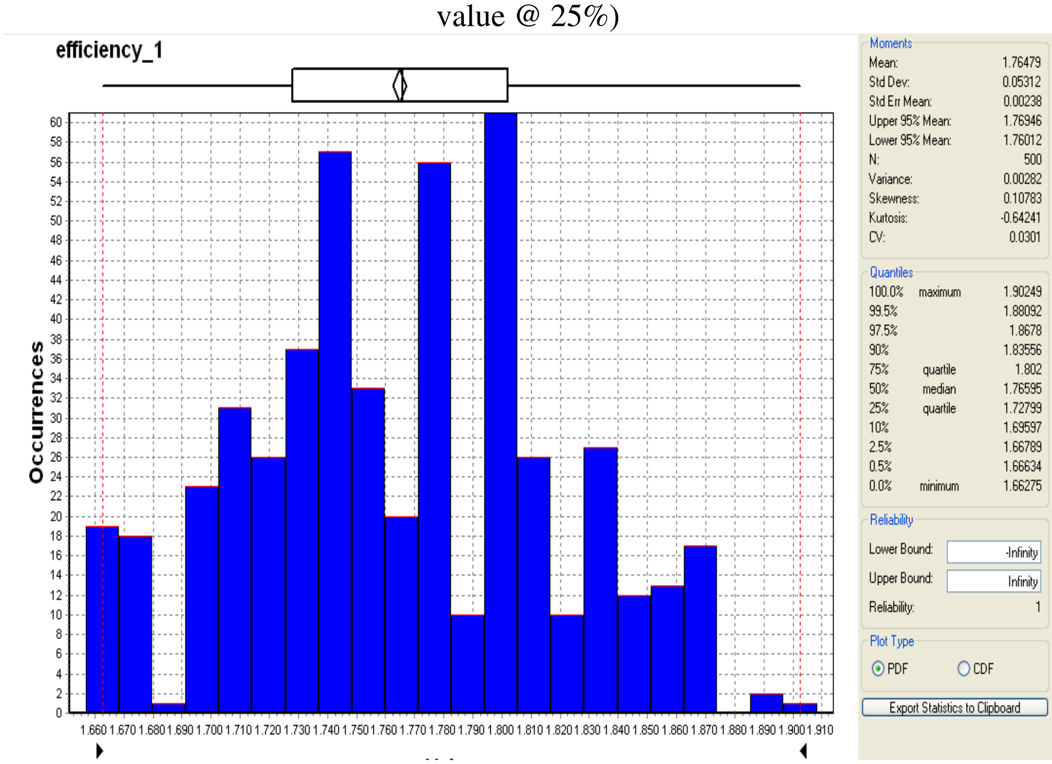


Figure 6.15: Distribution of Energy efficiency for the first year– System 1 (Mean value @ 25%)

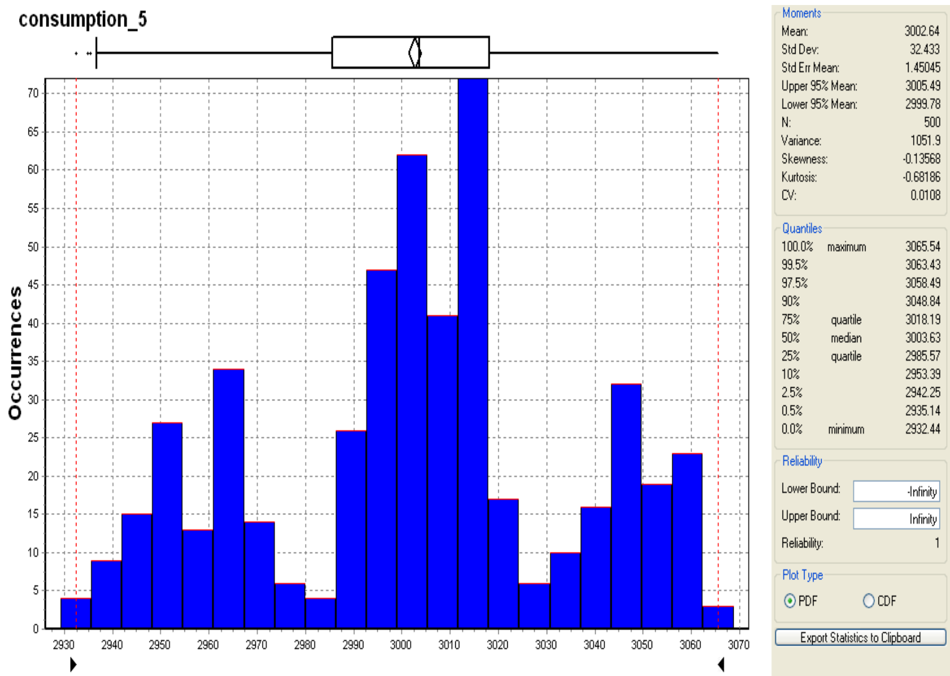


Figure 6.16: Distribution of Energy consumption for average 5 years– System 1 (Mean value @ 25%)

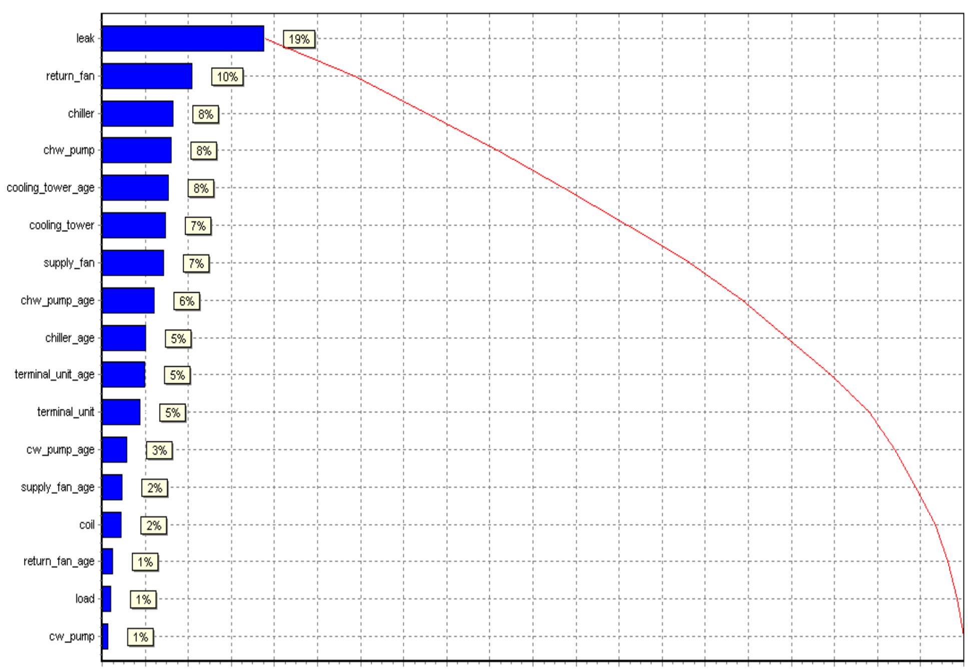


Figure 6.17: Energy analysis results– System 1 (Mean value @ 25%)

Results from the sensitivity analyses in each set of simulation and the average of all simulations have been tabulated in Table 6.2. These results show that top influential components for efficiency of system1 are amount of leakage from the ducts, terminal unit degradation degree, chilled water pump, chilled water pump degradation, chiller and chiller degradation degree. As shown test tolerances move (in the mean) closer to the base performance the amount of leakage in the system moves up in the parameter sensitivity ranking, while Chilled water pump and Chiller compressor are less sensitive to this and keep their relatively high sensitivity compared to other components.

Table 6.2: System 1 sensitivity analysis (bin size) results (relevance of component)

| System 1 Components | Occurrence of 75% mean deviation | Occurrence of 50% mean deviation | Occurrence of 25% mean deviation | Average deviation |
|---|---|---|---|---|
| Duct Air Leakage | 2 | 12 | 19 | 6.7 |
| CHWP | 10 | 8 | 8 | 9.2 |
| CHWP age | 11 | 8 | 6 | 9.6 |
| Chiller age | 8 | 11 | 5 | 8.6 |
| Chiller age | 8 | 8 | 8 | 8 |
| Terminal Unit age | 12 | 4 | 5 | 8.9 |
| Cooling Tower | 7 | 5 | 7 | 6.4 |
| CWP age | 7 | 8 | 3 | 6.9 |
| Cooling Tower AGE | 9 | 1 | 8 | 6.5 |
| Coil | 3 | 12 | 2 | 5.6 |
| Return Fan age | 10 | 5 | 1 | 3.4 |
| Supply Fan | 3 | 3 | 7 | 7.6 |
| Return Fan | 1 | 1 | 10 | 3.1 |
| Terminal Units | 0 | 4 | 5 | 2.3 |
| Load | 3 | 4 | 1 | 1.3 |
| CWP age | 3 | 4 | 2 | 3.4 |
| Supply Fan age | 3 | 2 | 2 | 3.2 |

Based on the outcome of the sensitivity analysis, another experiment, was performed in which we decreased the maximum allowable tolerance of the chiller. As this is one of the most influential components in this system we decreased it to half of the performance deviation permitted by the ARI standard. We performed multiple Monte Carlo simulations for the improved system and compared the results of the original simulation with the improved system. The simulation results show that by cutting the allowable performance deviation of the chiller by half while keeping all other components in their original values, the chances that the improved system consumes less energy than the lowest level of energy consumption of the original system in the first year increases by 9.6%. Also the highest level of energy consumption of the improved system decreases by 25.2% compared to the energy consumption of the original system (See Table 6.3 below). By using this analysis, we see by selecting the most influential component in our targeted system and pursuing the testing agency and equipment manufacturer of this element to set a stricter standard and deliver an equipment whose maximum performance deviation is half of the one currently allowance by the testing agencies, we could decrease the total system energy consumption by as much as 1.7% (see Table B1 in Appendix B).

Table 6.3: System 1 energy consumption improvement

| Consumption | % After Improvement | % Before Improvement |
|---|---|---|
| 2900 | 0.27 | 0.00 |
| 2910 | 1.33 | 0.00 |
| 2920 | 3.07 | 0.00 |
| 2930 | 5.00 | 0.00 |
| 2940 | 0.40 | 8.27 |
| 2950 | 2.47 | 0.00 |
| 2960 | 7.33 | 8.80 |
| 2970 | 7.87 | 0.00 |
| 2980 | 8.53 | 9.80 |
| 2990 | 4.47 | 0.00 |
| 3000 | 2.40 | 7.20 |
| 3010 | 7.53 | 0.00 |
| 3020 | 6.33 | 8.07 |
| 3030 | 5.47 | 0.00 |
| 3040 | 5.00 | 5.40 |
| 3050 | 1.87 | 0.00 |
| 3060 | 7.13 | 6.47 |
| 3070 | 2.00 | 0.00 |
| 3080 | 10.00 | 3.27 |
| 3090 | 0.33 | 0.00 |
| 3100 | 2.20 | 3.40 |
| 3110 | 0.00 | 0.00 |
| 3120 | 4.27 | 8.20 |
| 3130 | 0.00 | 0.00 |
| 3140 | 4.00 | 5.13 |
| 3150 | 0.00 | 0.00 |
| 3160 | 0.40 | 5.60 |
| 3170 | 0.00 | 0.00 |
| 3180 | 0.20 | 6.87 |
| 3190 | 0.00 | 0.00 |
| 3200 | 0.00 | 4.67 |

Table 6.3. Continued

| | | |
|---|---|---|
| 3210 | 0.00 | 0.00 |
| 3220 | 0.13 | 2.47 |
| 3230 | 0.00 | 0.00 |
| 3240 | 0.00 | 5.67 |
| 3250 | 0.00 | 0.00 |
| 3260 | 0.00 | 0.67 |
| 3270 | 0.00 | 0.00 |
| 3280 | 0.00 | 0.07 |

The results which are tabulated in the above table have been presented in a graphical presentation in chart below.

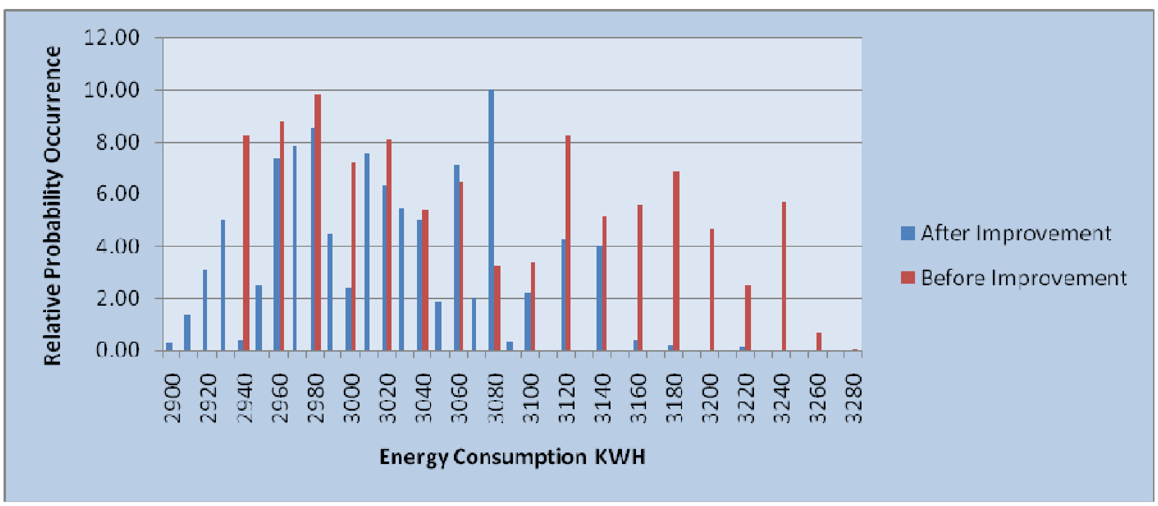


Figure 6.18: System 1 energy consumption improvement

Also from Table 6.3, it can be seen that there is a 25% chance that the peak energy consumption of the original system could be up to 4.2% higher than the maximum energy consumption of the improved system. This could be a crucial cost issue, since most of the utility providers, set the base charging price of the electricity for a building based on the maximum usage (peak) of the electricity.

Table 6.4: System 1 energy consumption comparison deterministic vs. probabilistic

| Deterministic kwh | Probabilistic kwh | % Difference | Occurrence | % Probability | % Cumulative |
|---|---|---|---|---|---|
| 2929 | | | | | |
| | 2940 | 0.38 | 12.4 | 2.48 | 100 |
| | 2960 | 1.06 | 13.4 | 2.68 | 97.52 |
| | 2980 | 1.74 | 17.7 | 3.54 | 94.84 |
| | 3000 | 2.42 | 25.4 | 5.08 | 91.3 |
| | 3020 | 3.11 | 21.1 | 4.22 | 86.22 |
| | 3040 | 3.79 | 27.2 | 5.44 | 82 |
| | 3060 | 4.47 | 53.1 | 10.62 | 76.56 |
| | 3080 | 5.16 | 27 | 5.4 | 65.94 |
| | 3100 | 5.84 | 29.1 | 5.82 | 60.54 |
| | 3120 | 6.52 | 56.7 | 11.34 | 54.72 |
| | 3140 | 7.20 | 24.6 | 4.92 | 43.38 |
| | 3160 | 7.89 | 31.5 | 6.3 | 38.46 |
| | 3180 | 8.57 | 40.2 | 8.04 | 32.16 |
| | 3200 | 9.25 | 40.8 | 8.16 | 24.12 |
| | 3220 | 9.94 | 22.3 | 4.46 | 15.96 |
| | 3240 | 10.62 | 51 | 10.2 | 11.5 |
| | 3260 | 11.30 | 6 | 1.2 | 1.3 |
| | 3280 | 11.98 | 0.5 | 0.1 | 0.1 |
| | | | 500 | | |

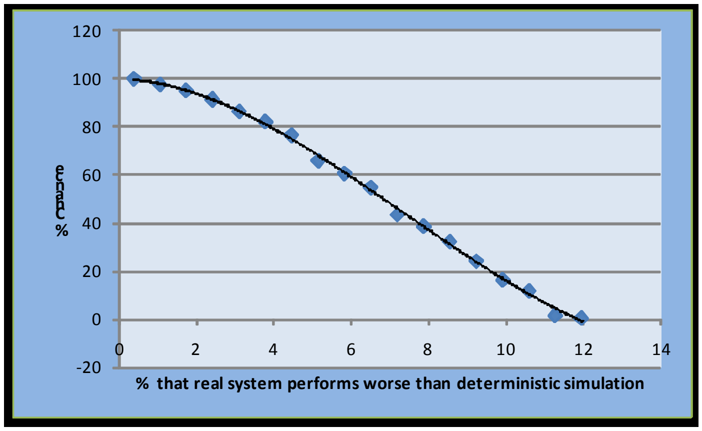


Figure 6.19: System 1 energy consumption comparison deterministic vs. probabilistic

Another outcome of the uncertainty analysis is the ability of comparison of the deterministic versus probabilistic simulations. As it is shown in Table 6.4 there is a 11.5% chance that system 1 performs up to 10.62% worse than what a deterministic calculations could predict, and also there is 54% chance that system 1 performs up to 6.52% worse than what a deterministic calculations could predict. The significance of this outcome will be realized when it is used to question the validity of the current industry energy analyzing method. For example assume as a result of a deterministic simulation system 1 is shown to consume about $3000*10^6$ BTU/Year. In order that this system passes the current energy code requirement, this consumption should be equal or less than an imaginary base building energy consumption. Also assume that the baseline (imaginary and not affected by any uncertainty) building energy simulation shows the building consumption is also $3000*10^6$ BTU/Year also, and therefore the designed system is qualified as to pass the energy code requirements. While we have shown that there is 11.5% chance that the design building could consume up to $3345*10^6$ BTU/Year and there is a 54% chance that the design building could consume up to $3195*10^6$ BTU/Year.

By these calculations the designed building should not be qualified as a building that complies with the requirements of the energy standards. Therefore the performed analyses in this section and the resulted outcomes are our basis for the argument that current industry energy efficiency standard without considering the effects of uncertainty and specifically uncertainty in the equipment test tolerances is not reliable. It can be said that, due to the probabilistic nature of the real systems, the deterministic simulations may in some cases create ground for qualification of buildings that in real life should not be qualified as energy efficient buildings.

It is interesting to check the influence of the size of the system. For this reason we looked at office buildings with twice and three times larger cooling loads and ventilation requirement than the reference building studied above. We tag the systems as 1, 1A and 1B respectively. We performed multiple Monte Carlo simulations and tabulated the sensitivity analysis results in respective tables. These sensitivity analyses results (comparison between systems 1, 1A and 1B) show that size only some, but moderate effect on overall system efficiency. The sensitivity shows that the ranking of the most influential components significantly however, from e.g. coil and chiller degradation (age) to chilled water pump and chilled water pump degradation respectively. (Figure 6.20 bellow)

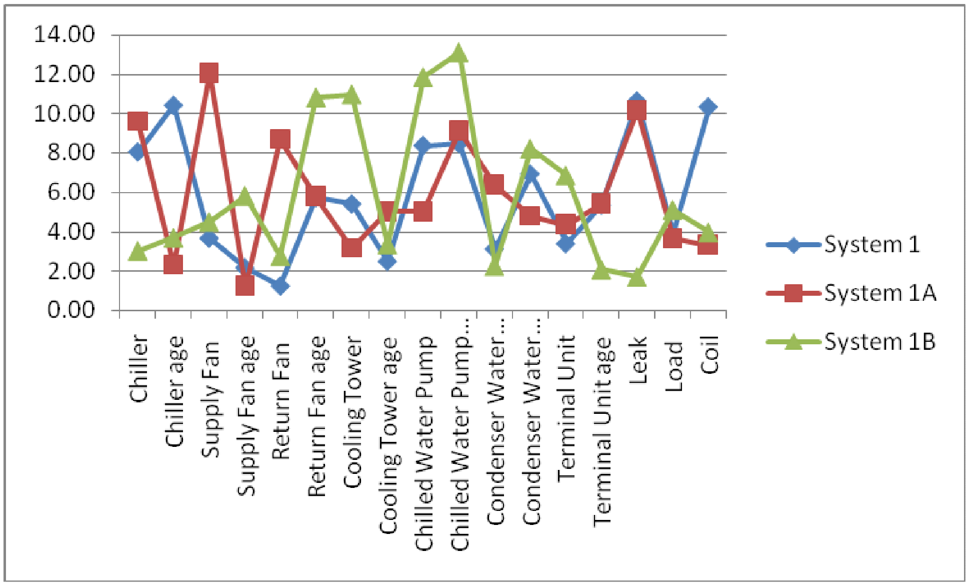


Figure 6.20: System 1 component sensitivity changes as the system size changes

Using the results from the above simulations for the systems sizes 1, 1A (twice as large as system 1), and 1B (three times larger than system 1) we evaluated the effects of increasing system size on the sensitivity of the equipment. In other word we came up with a pattern that shows for each system (e.g. system 1), as we increase the size (capacity) of the system, which elements contribute to the overall system energy consumption. To do so we tabulate the results of sensitivity analyses on three systems capacities for system 1 (1, 1A and 1B) and then calculated the correlation of each element's sensitivity analysis result against the increasing size of the system (see Table 6.5 below). For system 1 it appears that as we increase the size of the system the highest positive and highest negative effects come from terminal units and leakage respectively. It means it is likely that as the system size increases, effects of terminal units on the uncertainty of overall ECaE of the system increases and effects of leakage on uncertainty of overall ECaE of the system decreases.

Table 6.5: System 1 component sensitivity correlation with system capacity changes

| Capacity | Chiller age | Chiller | Supply Fan | Supply Fan age | Return Fan | Return Fan age | Cooling Tower | Cooling Tower age | |
|---|---|---|---|---|---|---|---|---|---|
| 150 | 10.44 | 8.07 | 3.68 | 2.18 | 1.25 | 5.75 | 5.42 | 2.51 | |
| 300 | 2.3 | 9.6 | 12.06 | 1.21 | 8.69 | 5.79 | 3.15 | 5.02 | |
| 450 | 3.69 | 3.03 | 4.49 | 5.82 | 2.76 | 10.81 | 10.97 | 3.35 | |
| corr. | -0.78 | -0.73 | 0.09 | 0.75 | 0.19 | 0.87 | 0.69 | 0.33 | |
| Capacity | CHWP | CHWP age | CWP | CWP age | TU | TU age | Load | Leak | Coil |
| 150 | 8.39 | 8.5 | 3.13 | 6.95 | 3.41 | 5.37 | 3.95 | 10.65 | 10.35 |
| 300 | 5.02 | 9.13 | 6.36 | 4.77 | 4.36 | 5.4 | 3.65 | 10.17 | 3.32 |
| 450 | 11.85 | 13.09 | 2.26 | 8.21 | 6.85 | 2.07 | 5.1 | 1.7 | 3.96 |
| corr. | 0.51 | 0.92 | -0.20 | 0.36 | 0.97 | -0.86 | 0.75 | -0.89 | -0.82 |

Table 6.6: System 1 (Office) Uncertainty

| tons | Probabilistic Mean Consumption-kwh | Deterministic kwh | System 1 Average Performance Drop |
|---|---|---|---|
| 150 | 3188 | 2929 | 8.84% |
| 300 | 6383.6 | 5858 | 8.97% |
| 450 | 9559.8 | 8787 | 8.79% |

The performed analyses in this section and the outcomes are our basis for the argument that current industry energy efficiency standards can be improved. The improvement can come from considering and including the effects of uncertainty and specifically uncertainty in the equipment test tolerances. The changes can be resulted in better system selections, and higher acceptable standards that by itself will result in lower energy consumption and saving energy.

For the sensitivity analysis results for systems 1 through 6 for the healthcare model see Appendix E, Tables E1 through E6.

### 6.2.2. System 2: Variable volume air, with air cooled chillers

The main energy consuming components of this system are supply fan, return fan, terminal units fans, air cooled chiller (compressor), air cooled chiller (condenser) fan, and chilled water pump. Performance curves for each of these main components have been selected from the library of Trane Trace 700 software, two performance curves for water cooled centrifugal chillers, two performance curves for supply fans, two performance curves for return fans, two performance curves for condenser fans, one performance curve for terminal unit, and one performance curve for chilled water pump. In each case family of the performance curves based on gradual increase of 0.5 or 1% tolerance from the curve default value up to the maximum allowable test tolerance based on ARI and HI standards have been generated.

Peak load condition of the equipment for the default curve on both deterministic and probabilistic calculations has been derived from the acceptable maximum power consumption from ASHRAE 90.1. (See Table 6.7 below)

Table 6.7: System 2 component efficiency@ full load condition

| Component | Efficiency @ full load | Reference |
|---|---|---|
| Variable Volume Fan | hp = cfm * 0.0015 | ASHRAE 90.1 2010, Table 6.5.3.1.1A |
| Constant Volume Fan (Terminal Units) | hp = cfm* 0.0011 | ASHRAE 90.1 2010, Table 6.5.3.1.1A |
| Air Cooled Chiller Compressor | 9.562 EER | ASHRAE 90.1 2010, Table 6.8.1C |
| Air Cooled Chiller Condenser Fan | 176000 Btuh/hp | ASHRAE 90.1 2010, Table 6.8.1G |
| Chilled Water Pump | 22 Watts/ gpm | ASHRAE 90.1 2010, Section G3.1.3.10 |

Results from sensitivity analyses in each set of simulation and also the average of all simulations have been tabulated in Table 6.8. These results show that top influential component for efficiency of the system 2 is the compressor.

Table 6.8: System 2 sensitivity analysis (bin size) results (relevance of component)

| System 2 Components | Occurrence of 75% Deviation | Occurrence of 50% Deviation | Occurrence of 25% Deviation | Average Deviation |
|---|---|---|---|---|
| Compressor | 15 | 19 | 8 | 15.5 |
| Terminal Units | 9 | 12 | 6 | 9.6 |
| Return Fan age | 12 | 3 | 10 | 9.1 |
| Condenser Fan | 6 | 6 | 10 | 6.4 |
| CHWP | 6 | 5 | 10 | 6.1 |
| Coil | 1 | 8 | 12 | 4.2 |
| Return Fan | 5 | 10 | 6 | 6.6 |
| Leak | 13 | 1 | 5 | 8.6 |
| Condenser Fan | 1 | 8 | 8 | 3.8 |
| Load | 6 | 9 | 2 | 6.5 |
| Supply Fan age | 8 | 1 | 7 | 5.8 |
| CHWP age | 7 | 5 | 3 | 6 |
| Compressor age | 5 | 8 | 2 | 5.6 |
| Terminal Unit age | 6 | 3 | 5 | 5 |
| Supply Fan | 0 | 3 | 7 | 1.6 |

Based on the outcome of this sensitivity analysis, in another experiment, we decreased the maximum allowable tolerance of the compressor as the most influential component in this system to half of the permitted test tolerance by ARI standard. We performed multiple Monte Carlo simulations for the improved system and compared the results of the original simulation with the improved system. The simulation results show that by cutting the allowable test tolerance of the compressor by half while keeping all other components in their original values, chances that the improved system consumes less energy than lowest level of energy consumption of the original system in first year increases by 3%. Also the highest level of energy consumption of the improved system decreases by 26.5% compared to the energy consumption of the original system (See Table 6.9 below). By using this analysis, we see that by selecting the most influential component in our targeted system and pursuing the equipment manufacturer of this element to deliver an equipment that its maximum test tolerance performance is half of the allowance by the testing agencies, we could decrease the total system energy consumption by as much as 1.25% (see Table B2 in Appendix B).

Table 6.9: System 2 energy consumption improvement

| Energy Consumption KWH | % After improvement | % Before improvement |
|---|---|---|
| 3720 | 0.00 | 0.00 |
| 3730 | 0.00 | 0.00 |
| 3740 | 0.00 | 0.00 |
| 3750 | 0.00 | 0.00 |
| 3760 | 0.00 | 0.00 |

Table 6.9. Continued

| | | |
|---|---|---|
| 3770 | 0.07 | 0.00 |
| 3780 | 3.47 | 0.00 |
| 3790 | 3.13 | 0.33 |
| 3800 | 6.27 | 1.13 |
| 3810 | 9.73 | 3.13 |
| 3820 | 8.00 | 5.67 |
| 3830 | 3.07 | 8.67 |
| 3840 | 2.13 | 6.33 |
| 3850 | 3.53 | 5.20 |
| 3860 | 5.20 | 2.47 |
| 3870 | 8.80 | 0.60 |
| 3880 | 5.93 | 1.13 |
| 3890 | 4.40 | 2.27 |
| 3900 | 1.67 | 4.47 |
| 3910 | 2.20 | 5.07 |
| 3920 | 1.93 | 7.13 |
| 3930 | 5.00 | 5.33 |
| 3940 | 4.80 | 4.80 |
| 3950 | 5.40 | 1.87 |
| 3960 | 8.40 | 1.07 |
| 3970 | 3.60 | 0.27 |
| 3980 | 2.47 | 1.40 |
| 3990 | 0.73 | 1.60 |
| 4000 | 0.07 | 4.07 |
| 4010 | 0.00 | 3.67 |
| 4020 | 0.00 | 7.13 |
| 4030 | 0.00 | 3.93 |
| 4040 | 0.00 | 5.73 |
| 4050 | 0.00 | 2.40 |
| 4060 | 0.00 | 1.93 |
| 4070 | 0.00 | 0.67 |
| 4080 | 0.00 | 0.53 |
| 4090 | 0.00 | 0.00 |
| 4100 | 0.00 | 0.00 |

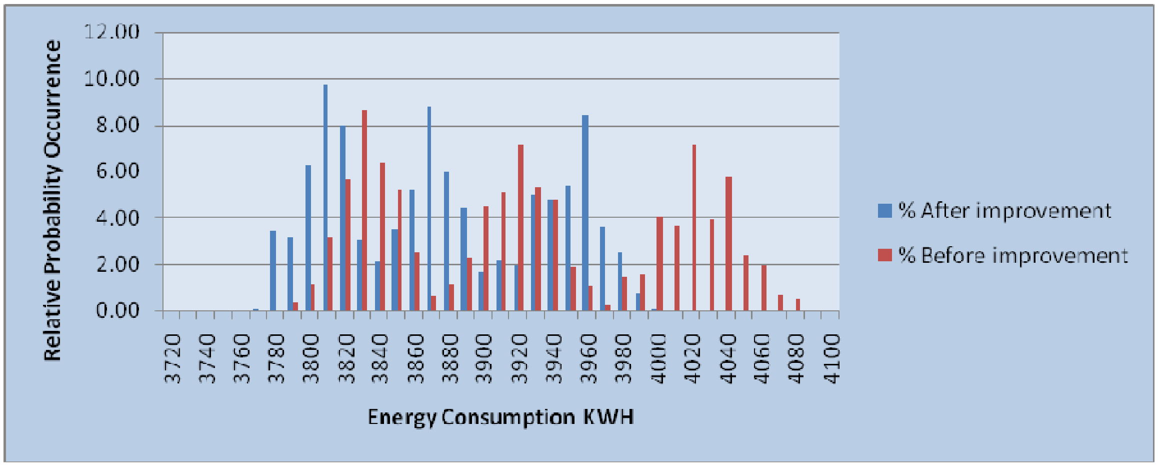


Figure 6.21: System 2 energy consumption improvement

Table 6.10: System 2 energy consumption comparison deterministic vs. probabilistic

| Deterministic kwh | Probabilistic kwh | % Difference | Occurrence | % Probability | % Cumulative |
|---|---|---|---|---|---|
| 3773 | | | | | |
| | 3790 | 0.45 | 0.5 | 0.1 | 100 |
| | 3800 | 0.72 | 1.7 | 0.34 | 99.9 |
| | 3810 | 0.98 | 4.7 | 0.94 | 99.56 |
| | 3820 | 1.25 | 8.5 | 1.7 | 98.62 |
| | 3830 | 1.51 | 13 | 2.6 | 96.92 |
| | 3840 | 1.78 | 9.5 | 1.9 | 94.32 |
| | 3850 | 2.04 | 7.8 | 1.56 | 92.42 |
| | 3860 | 2.31 | 3.7 | 0.74 | 90.86 |
| | 3870 | 2.57 | 1.5 | 0.3 | 90.12 |
| | 3880 | 2.84 | 5.1 | 1.02 | 89.82 |
| | 3890 | 3.10 | 10.2 | 2.04 | 88.8 |
| | 3900 | 3.37 | 20.1 | 4.02 | 86.76 |
| | 3910 | 3.63 | 22.8 | 4.56 | 82.74 |
| | 3920 | 3.90 | 32.1 | 6.42 | 78.18 |
| | 3930 | 4.16 | 24 | 4.8 | 71.76 |
| | 3940 | 4.43 | 21.6 | 4.32 | 66.96 |

Table 6.10. Continued

| | | | | | |
|---|---|---|---|---|---|
| | 3950 | 4.69 | 8.7 | 1.74 | 62.64 |
| | 3960 | 4.96 | 5.1 | 1.02 | 60.9 |
| | 3970 | 5.22 | 1.8 | 0.36 | 59.88 |
| | 3980 | 5.49 | 12.6 | 2.52 | 59.52 |
| | 3990 | 5.75 | 14.4 | 2.88 | 57 |
| | 4000 | 6.02 | 36.6 | 7.32 | 54.12 |
| | 4010 | 6.28 | 33 | 6.6 | 46.8 |
| | 4020 | 6.55 | 64.2 | 12.84 | 40.2 |
| | 4030 | 6.81 | 35.4 | 7.08 | 27.36 |
| | 4040 | 7.08 | 51.6 | 10.32 | 20.28 |
| | 4050 | 7.34 | 21.6 | 4.32 | 9.96 |
| | 4060 | 7.61 | 17.4 | 3.48 | 5.64 |
| | 4070 | 7.87 | 6 | 1.2 | 2.16 |
| | 4080 | 8.14 | 4.8 | 0.96 | 0.96 |
| | | | 500 | | |

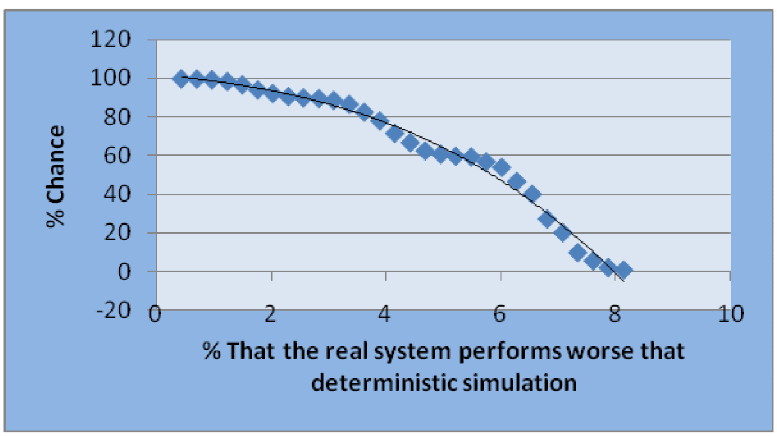


Figure 6.22: System 2 energy consumption comparison deterministic vs. probabilistic

Another outcome of this uncertainty analysis is the ability of comparison of the deterministic versus probabilistic simulations. As it is shown in Table 6.10, and Figure 6.22 we can see that e.g. there is a 20.2% chance that system 2 performs up to 7.08%

worse than what a deterministic calculations could predict, and there is 60% chance that system 2 performs up to 5.22% worse than what a deterministic calculations could predict. The significance of this outcome will be realized when it is used as a supplemental information to the current industry energy analysis reports.

On a separate simulation we used system 2 as the base for office buildings with twice and three times larger cooling loads, and ventilation requirement and tagged the systems as 2, 2A and 2B respectively.

Table 6.11: System 2 (Office) Uncertainty

| tons | Probabilistic Mean Consumption-kwh | Deterministic kwh | System 2 Average Performance Drop |
|---|---|---|---|
| 150 | 4071.7 | 3773 | 7.92% |
| 300 | 8143.7 | 7546 | 7.92% |
| 450 | 12216.4 | 11319 | 7.93% |

For detail simulation results for system 2, see related tables in Appendices A and B.

### 6.2.3. System 3: Variable Volume Air Packaged Rooftop Unit

This unit is self-contained factory fabricated unitary equipment. The major energy consuming components of this system are of supply fan, return/exhaust fan, compressors, condenser fan, and terminal units. Air is distributed from the unit through the ductwork to terminal units and from there to the space. Terminal units could be of either valve or fan type. Terminal unit fans are of constant volume type. The benefits of this system are lower initial cost, and no need for wasting space for interior mechanical rooms. Disadvantages of these systems are higher maintenance cost, limited capacity and requirement of supported roof structure.

Performance curves for each of these main components have been selected from the library of Trane Trace 700 software, two performance curves for compressors, two performance curves for supply fans, two performance curves for return fans, two performance curves for condenser fans, and one performance curve for terminal units. In each case family of the performance curves based on gradual increase of 0.5 or 1% tolerance from the curve default value up to the maximum allowable test tolerance based on ARI and HI standards have been generated.

Peak load condition of the equipment for the default curve on both deterministic and probabilistic calculations has been derived from the acceptable maximum power consumption from ASHRAE 90.1. (See Table 6.12 below)

Table 6.12: System 3 component efficiency@ full load condition

| **Component** | **Efficiency @ full load** | **Reference** |
|---|---|---|
| Variable Volume Fan | hp = cfm * 0.0015 | ASHRAE 90.1 2010, Table 6.5.3.1.1A |
| Constant Volume Fan (Terminal Units) | hp = cfm* 0.0011 | ASHRAE 90.1 2010, Table 6.5.3.1.1A |
| Compressor | 9.5 EER | ASHRAE 90.1 2010, Table 6.8.1A |
| Condenser Fan | 176000 Btuh/hp | ASHRAE 90.1 2010, Table 6.8.1G |

Results from sensitivity analyses in each set of simulation and also the average of all simulations have been tabulated in Table 6.13. These results show that top influential component for efficiency of the system 3 is the compressor.

Table 6.13: System 3 sensitivity analysis results (relevance of component)

| System 3 Components | Occurrence of 75% Deviation | Occurrence of 50% Deviation | Occurrence of 25% Deviation | Average Occurrence |
|---|---|---|---|---|
| Compressor | 82 | 19 | 1 | 55 |
| Supply Fan age | 4 | 10 | 5 | 5.9 |
| Coil | 2 | 5 | 9 | 3.6 |
| Terminal Unit age | 0 | 2 | 5 | 1.1 |
| Supply Fan age | 1 | 4 | 15 | 3.3 |
| Return Fan age | 1 | 5 | 9 | 3 |
| Return Fan | 0 | 4 | 19 | 3.1 |
| Condenser Fan age | 2 | 6 | 4 | 3.4 |
| Terminal Units | 0 | 12 | 0 | 3.6 |
| Condenser Fan | 0 | 8 | 13 | 3.7 |
| Compressor age | 4 | 10 | 8 | 6.2 |
| Leak | 2 | 3 | 4 | 2.5 |
| Load | 1 | 13 | 7 | 5.2 |

Based on the outcome of this sensitivity analysis, in another experiment, we decreased the maximum allowable tolerance of the compressor as the most influential component in this system to half of the permitted test tolerance by ARI standard. We performed multiple Monte Carlo simulations for the improved system and compared the results of the original simulation with the improved system. The simulation results show that by cutting the allowable test tolerance of the compressor by half while keeping all other components in their original values, the highest level of energy consumption of the improved system decreases by 8.7% compared to the energy consumption of the original system. By using this analysis, we see that by selecting the most influential component in our targeted system and pursuing the equipment manufacturer of this element to deliver an equipment that its maximum test tolerance performance is half of the allowance by the testing agencies, we could decrease the total system energy consumption by as much as 10.8% (see Table B3 in Appendix B).

Table 6.14: System 3 energy consumption comparison deterministic vs. probabilistic

| Deterministic kwh | Probabilistic kwh | % Difference | Occurrence | % Probability | % Cumulative |
|---|---|---|---|---|---|
| 4002 | | | | | |
| | 3050 | -23.79 | 3 | 0.6 | 0.6 |
| | 4010 | 0.20 | 2.5 | 0.5 | 99.4 |
| | 4020 | 0.45 | 5.8 | 1.16 | 98.9 |
| | 4030 | 0.70 | 12.6 | 2.52 | 97.74 |
| | 4040 | 0.95 | 13.7 | 2.74 | 95.22 |
| | 4050 | 1.20 | 8 | 1.6 | 92.48 |
| | 4060 | 1.45 | 6.3 | 1.26 | 90.88 |
| | 4070 | 1.70 | 1.1 | 0.22 | 89.62 |
| | 4080 | 1.95 | 0 | 0 | 89.4 |
| | 4090 | 2.20 | 0.3 | 0.06 | 89.4 |
| | 4100 | 2.45 | 2.1 | 0.42 | 89.34 |
| | 4110 | 2.70 | 15.6 | 3.12 | 88.92 |
| | 4120 | 2.95 | 21 | 4.2 | 85.8 |
| | 4130 | 3.20 | 32.7 | 6.54 | 81.6 |
| | 4140 | 3.45 | 13.8 | 2.76 | 75.06 |
| | 4150 | 3.70 | 21 | 4.2 | 72.3 |
| | 4160 | 3.95 | 20.1 | 4.02 | 68.1 |
| | 4170 | 4.20 | 7.8 | 1.56 | 64.08 |

Table 6.14. Continued

| | | | | | |
|---|---|---|---|---|---|
| | 4180 | 4.45 | 5.1 | 1.02 | 62.52 |
| | 4190 | 4.70 | 8.4 | 1.68 | 61.5 |
| | 4200 | 4.95 | 228 | 45.6 | 59.82 |
| | 4210 | 5.20 | 0.3 | 0.06 | 14.22 |
| | 4250 | 6.20 | 0 | 0 | 14.16 |
| | 4300 | 7.45 | 70.8 | 14.16 | 14.16 |
| | | | 500 | | |

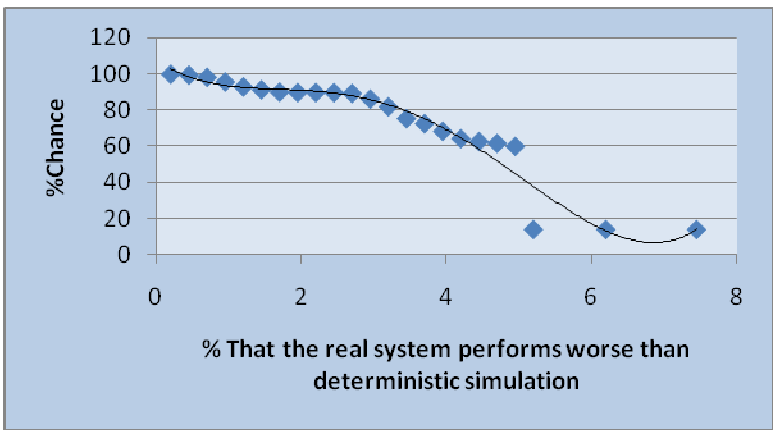


Figure 6.23: System 3 energy consumption comparison deterministic vs. probabilistic

Another outcome of this uncertainty analysis is the ability of comparison of the deterministic versus probabilistic simulations. As it is shown in Table 6.14 and Figure 6.23 we can see that e.g. there is a 14.16% chance that system 3 performs up to 7.45% worse than what a deterministic calculations could predict, and there is 81% chance that system 3 performs up to 3.2% worse than what a deterministic calculations could predict. The significance of this outcome will be realized when it is used as a supplemental information to the current industry energy analysis reports.

On a separate simulation we used system 3 as the base for office buildings with twice and three times larger cooling loads, and ventilation requirement and tagged the systems as 3, 3A and 3B respectively.

Table 6.15: System 3 (Office) Uncertainty

| tons | Probabilistic Mean Consumption-kwh | Deterministic kwh | System 3 Average Performance Drop |
|---|---|---|---|
| 150 | 4217.3 | 4002 | 5.38% |
| 300 | 8583.9 | 8004 | 7.25% |
| 450 | 12894.8 | 12006 | 7.40% |

For detail simulation results for system 3, see related tables in Appendices A and B.

### 6.2.4. System 4: Self-Contained Water-Cooled Air Conditioner

The main energy consuming components of this system are supply fan, return/exhaust fan, compressor, cooling tower fan, condenser water pump and terminal units. Cooling tower and condenser pumps provide means of removing the heat from the condenser. System is usually variable volume with variable frequency drive. Constant volume systems are also available. Air from self-contained unit is delivered to the space through ductwork and terminal units. Advantages of this unit are that they occupy less space compare to systems with separate chiller plant, and multiple use of them eliminates the requirements of the large and vertical ducts. These units are required to be close to an exterior wall for outside air intake, and also need a separate return fan system.

Performance curves for each of these main components have been selected from the library of Trane Trace 700 software, two performance curves for water cooled compressor, two performance curves for supply fans, two performance curves for return fans, two performance curves for condenser fans, one performance curve for terminal units, and one performance curve for condenser water pump. In each case family of the performance curves based on gradual increase of 0.5 or 1% tolerance from the curve default value up to the maximum allowable test tolerance based on ARI and HI standards have been generated.

Peak load condition of the equipment for the default curve on both deterministic and probabilistic calculations has been derived from the acceptable maximum power consumption from ASHRAE 90.1. (See Table 6.16 below)

Table 6.16: System 4 component efficiency@ full load condition

| **Component** | **Efficiency @ full load** | **Reference** |
|---|---|---|
| Variable Volume Fan | hp = cfm * 0.0015 | ASHRAE 90.1 2010, Table 6.5.3.1.1A |
| Constant Volume Fan (Terminal Units) | hp = cfm* 0.0011 | ASHRAE 90.1 2010, Table 6.5.3.1.1A |
| Water cooled Compressor | 12 EER | ASHRAE 90.1 2010, Table 6.8.1A |
| Condenser Fan | 176000 Btuh/hp | ASHRAE 90.1 2010, Table 6.8.1G |
| Condenser Water Pump | 19 Watts/ gpm | ASHRAE 90.1 2010, Section G3.1.3.10 |

Results from sensitivity analyses in each set of simulation and also the average of all simulations have been tabulated in Table 6.17. These results show that top influential components for efficiency of the system 4 are effects of aging on terminal units, return fan, condenser water pump, terminal unit and compressor.

Table 6.17: System 4 sensitivity analysis (bin size) results (relevance of component)

| System 4 Components | Occurrence of 75% Deviation | Occurrence of 50% Deviation | Occurrence of 25% Deviation | Average Occurrence |
|---|---|---|---|---|
| Compressor | 3 | 17 | 13 | 8.2 |
| Terminal Unit | 4 | 20 | 5 | 8.9 |
| Return Fan age | 14 | 2 | 12 | 10.2 |
| Load | 3 | 5 | 18 | 5.1 |
| Terminal Unit age | 13 | 11 | 1 | 11.2 |
| CWP age | 3 | 7 | 10 | 4.9 |
| Return Fan | 8 | 3 | 8 | 6.5 |
| Condenser Fan age | 1 | 5 | 11 | 3.2 |
| Compressor age | 12 | 2 | 3 | 8.1 |
| Leak | 5 | 9 | 3 | 6 |
| CWP age | 13 | 1 | 1 | 8.2 |
| Supply Fan | 3 | 5 | 7 | 4 |
| Coil | 6 | 8 | 0 | 6 |
| Condenser Fan | 4 | 6 | 2 | 4.4 |
| Supply Fan age | 5 | 1 | 6 | 3.9 |

Based on the outcome of this sensitivity analysis, in another experiment, we decreased the maximum allowable tolerance of the compressor in this system to half of the permitted test tolerance by ARI standard. We performed multiple Monte Carlo simulations for the improved system and compared the results of the original simulation with the improved system. By using this analysis, we see that by selecting the most influential component in our targeted system and pursuing the equipment manufacturer to comply with the, we could decrease the total system energy consumption by as much as 1.7% (see Table B4 in Appendix B).

Table 6.18: System 4 energy consumption comparison deterministic vs. probabilistic

| Deterministic kwh | Probabilistic kwh | % Difference | Occurrence | % Probability | % Cumulative |
|---|---|---|---|---|---|
| 3733 | | | | | |
| | 3720 | -0.35 | 0.9 | 0.18 | 0.18 |
| | 3730 | -0.08 | 4.2 | 0.84 | 1.02 |
| | 3740 | 0.19 | 8.6 | 1.72 | 98.98 |
| | 3750 | 0.46 | 3.2 | 0.64 | 97.26 |
| | 3760 | 0.72 | 0.2 | 0.04 | 96.62 |
| | 3770 | 0.99 | 4.5 | 0.9 | 96.58 |
| | 3780 | 1.26 | 10.5 | 2.1 | 95.68 |
| | 3790 | 1.53 | 7.5 | 1.5 | 93.58 |
| | 3800 | 1.79 | 9.5 | 1.9 | 92.08 |
| | 3810 | 2.06 | 0.8 | 0.16 | 90.18 |
| | 3820 | 2.33 | 0.3 | 0.06 | 90.02 |
| | 3830 | 2.60 | 0 | 0 | 89.96 |
| | 3840 | 2.87 | 0.3 | 0.06 | 89.96 |
| | 3850 | 3.13 | 0 | 0 | 89.9 |
| | 3860 | 3.40 | 0 | 0 | 89.9 |
| | 3870 | 3.67 | 0 | 0 | 89.9 |
| | 3880 | 3.94 | 0.6 | 0.12 | 89.9 |
| | 3890 | 4.21 | 0 | 0 | 89.78 |
| | 3900 | 4.47 | 6.9 | 1.38 | 89.78 |
| | 3910 | 4.74 | 0 | 0 | 88.4 |
| | 3920 | 5.01 | 41.4 | 8.28 | 88.4 |

Table 6.18. Continued

| | | | | | |
|---|---|---|---|---|---|
| | 3930 | 5.28 | 0 | 0 | 80.12 |
| | 3940 | 5.55 | 50.1 | 10.02 | 80.12 |
| | 3950 | 5.81 | 0 | 0 | 70.1 |
| | 3960 | 6.08 | 55.5 | 11.1 | 70.1 |
| | 3970 | 6.35 | 0 | 0 | 59 |
| | 3980 | 6.62 | 66 | 13.2 | 59 |
| | 3990 | 6.88 | 0 | 0 | 45.8 |
| | 4000 | 7.15 | 42.3 | 8.46 | 45.8 |
| | 4010 | 7.42 | 0 | 0 | 37.34 |
| | 4020 | 7.69 | 82.2 | 16.44 | 37.34 |
| | 4030 | 7.96 | 0 | 0 | 20.9 |
| | 4040 | 8.22 | 32.7 | 6.54 | 20.9 |
| | 4050 | 8.49 | 0 | 0 | 14.36 |
| | 4060 | 8.76 | 25.2 | 5.04 | 14.36 |
| | 4070 | 9.03 | 0 | 0 | 9.32 |
| | 4080 | 9.30 | 42.5 | 8.5 | 9.32 |
| | 4090 | 9.56 | 0 | 0 | 0.82 |
| | 4100 | 9.83 | 4.1 | 0.82 | 0.82 |
| | | | 500 | | |

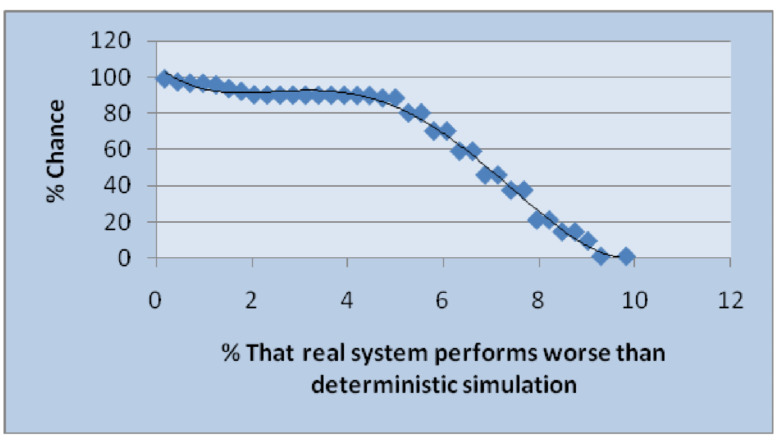


Figure 6.24: System 4 energy consumption comparison deterministic vs. probabilistic

Another outcome of this uncertainty analysis is the ability of comparison of the deterministic versus probabilistic simulations. As it is shown in Table 6.18 and Figure 6.24 we can see that e.g. there is a 14.36% chance that system 4 performs up to 8.76% worse than what a deterministic calculations could predict, and there is 80% chance that system 4 performs up to 5.55% worse than what a deterministic calculations could predict. The significance of this outcome will be realized when it is used as a supplemental information to the current industry energy analysis reports.

On a separate simulation we used system 4 as the base for office buildings with twice and three times larger cooling loads, and ventilation requirement and tagged the systems as 4, 4A and 4B respectively.

Table 6.19: System 4 (Office) Uncertainty

| tons | Probabilistic Mean Consumption-kwh | Deterministic kwh | System 4 Average Performance Drop |
|---|---|---|---|
| 150 | 4070.4 | 3733 | 9.04% |
| 300 | 8147.1 | 7466 | 9.12% |
| 450 | 12204.3 | 11199 | 8.98% |

For detail simulation results for system 4, see related tables in Appendices A and B.

### 6.2.5. System 5: Water Cooled Chillers with Fan Coil Units

In this system a chiller plant consists of chiller, cooling tower, chilled water and condenser water pumps provides chilled water to be used in small fan coils located throughout the building. Fan coil units have constant volume fans. Usually designers add a dedicated variable volume outdoor air unit to this system. The outdoor air unit consists of variable volume supply fan that provides required outside air to the fan coil units and variable volume exhaust fan that relief the excess air from the building. The most important advantages of fan coil system in a large building are that if some of the fan coils break-down the whole system does not need to stop and there is no need for dedicating large interior spaces to the air handling units, but the disadvantage is they are scattered through the building and need extra piping and service.

Performance curves for each of these main components have been selected from the library of Trane Trace 700 software, two performance curves for water cooled centrifugal chillers, two performance curves for supply fans, two performance curves for return fans, two performance curves for variable frequency type cooling tower fans, one performance curve for fan coil unit, one performance curve for chilled water pump and one performance curve for condenser water pump. In each case family of the performance curves based on gradual increase of 0.5 or 1% tolerance from the curve default value up to the maximum allowable test tolerance based on ARI and HI standards have been generated.

Peak load condition of the equipment for the default curve on both deterministic and probabilistic calculations has been derived from the acceptable maximum power consumption from ASHRAE 90.1. (See Table 6.20 below)

Table 6.20: System 1 component efficiency@ full load condition

| Component | Efficiency @ full load | Reference |
|---|---|---|
| Variable Volume Fan | hp = cfm * 0.0015 | ASHRAE 90.1 2010, Table 6.5.3.1.1A |
| Constant Volume Fan (Fan Coil Units) | hp = cfm* 0.0011 | ASHRAE 90.1 2010, Table 6.5.3.1.1A |
| Water Cooled Chiller (Centrifugal Compressor) | 0.634 kw/tons | ASHRAE 90.1 2010, Table 6.8.1C |
| Cooling Tower Fan | 20 gpm/hp | ASHRAE 90.1 2010, Table 6.8.1G |
| Chilled Water Pump | 22 Watts/ gpm | ASHRAE 90.1 2010, Section G3.1.3.10 |
| Condenser Water Pump | 19 Watts/ gpm | ASHRAE 90.1 2010, Section G3.1.3.11 |

Results from sensitivity analyses in each set of simulation and also the average of all simulations have been tabulated in Table 6.21. These results show that top influential components for efficiency of the system 5 are effects of aging on fan coil units, chilled water pump and outside air fan.

Table 6.21: System 5 sensitivity analysis (bin size) results (relevance of component)

| System 5 Components | Occurrence of 75% Deviation | Occurrence of 50% Deviation | Occurrence of 25% Deviation | Average Deviation |
|---|---|---|---|---|
| Fan Coil Unit age | 11 | 7 | 16 | 10.3 |
| CHWP age | 14 | 6 | 9 | 11.1 |
| O.A. Supply Fan age | 14 | 5 | 10 | 10.9 |
| Leak | 1 | 14 | 8 | 5.6 |
| CWP age | 15 | 6 | 1 | 10.9 |
| Coil | 0 | 14 | 8 | 5 |
| Fan Coil Units | 8 | 3 | 5 | 6.2 |
| Cooling Tower | 10 | 5 | 1 | 7.6 |
| Cooling Tower age | 3 | 5 | 7 | 4 |
| Load | 4 | 3 | 8 | 4.1 |

Table 6.21 Continued

| | | | | |
|---|---|---|---|---|
| Exhaust Fan age | 7 | 7 | 0 | 4.5 |
| Chiller | 3 | 8 | 3 | 6.9 |
| Chiller age | 4 | 0 | 7 | 2.5 |
| Exhaust Fan | 1 | 7 | 2 | 4.7 |
| O.A. Supply Fan | 1 | 0 | 7 | 1.3 |
| CWP age | 5 | 1 | 2 | 1.1 |
| CHWP age | 0 | 7 | 0 | 5.1 |

Based on the outcome of this sensitivity analysis, in another experiment, we decreased the maximum allowable tolerance of the fan coil unit aging as the most influential component in this system to half of the permitted test tolerance by ARI standard. We performed multiple Monte Carlo simulations for the improved system and compared the results of the original simulation with the improved system. By using this analysis, we see that by selecting the most influential component in our targeted system and pursuing the equipment manufacturer of this element to comply with the, we could decrease the total system energy consumption by as much as 0.35% (see Table B5 in Appendix B).

Table 6.22: System 5 energy consumption comparison deterministic vs. probabilistic

| Deterministic kwh | Probabilistic kwh | % Difference | Occurrence | % Probability | % Cumulative |
|---|---|---|---|---|---|
| 2338 | | | | | |
| | 2280 | -2.48 | 0.2 | 0.04 | 0.04 |
| | 2300 | -1.63 | 11.5 | 2.3 | 2.34 |
| | 2320 | -0.77 | 0.3 | 0.06 | 2.4 |
| | 2340 | 0.09 | 51 | 10.2 | 97.6 |
| | 2360 | 0.94 | 21.8 | 4.36 | 87.4 |
| | 2380 | 1.80 | 88.1 | 17.62 | 83.04 |

Table 6.22. Continued

| | | | | | |
|---|---|---|---|---|---|
| | 2400 | 2.65 | 40.3 | 8.06 | 65.42 |
| | 2420 | 3.51 | 52.2 | 10.44 | 57.36 |
| | 2440 | 4.36 | 26.7 | 5.34 | 46.92 |
| | 2460 | 5.22 | 11.4 | 2.28 | 41.58 |
| | 2480 | 6.07 | 30 | 6 | 39.3 |
| | 2500 | 6.93 | 24.6 | 4.92 | 33.3 |
| | 2520 | 7.78 | 67.5 | 13.5 | 28.38 |
| | 2540 | 8.64 | 15.6 | 3.12 | 14.88 |
| | 2560 | 9.50 | 55.2 | 11.04 | 11.76 |
| | 2580 | 10.35 | 3.6 | 0.72 | 0.72 |
| | | | 500 | | |

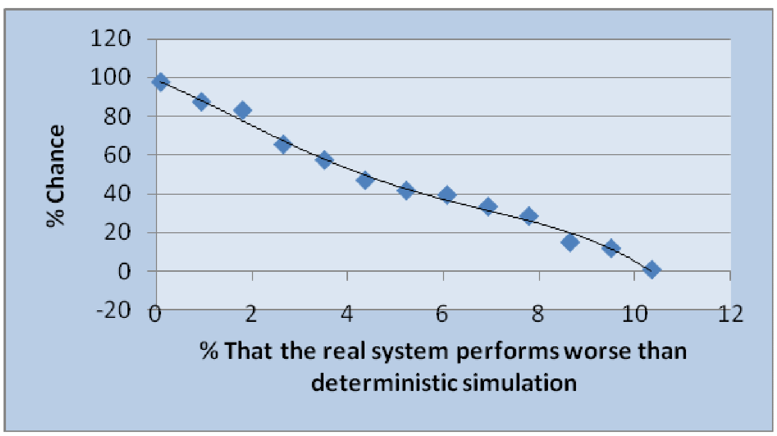


Figure 6.25: System 5 energy consumption comparison deterministic vs. probabilistic

Another outcome of this uncertainty analysis is the ability of comparison of the deterministic versus probabilistic simulations. As it is shown in Table 6.22 and Figure 6.25 we can see that e.g. there is a 11.76% chance that system 5 performs up to 9.5% worse than what a deterministic calculations could predict, and there is 57% chance that system 5 performs up to 3.51% worse than what a deterministic calculations could predict. The significance of this outcome will be realized when it is used as a supplemental information to the current industry energy analysis reports.

On a separate simulation we used system 5 as the base for office buildings with twice and three times larger cooling loads, and ventilation requirement and tagged the systems as 5, 5A and 5B respectively.

Table 6.23: System 5 (Office) Uncertainty

| tons | Probabilistic Mean Consumption-kwh | Deterministic kwh | System 5 Average Performance Drop |
|---|---|---|---|
| 150 | 2499.1 | 2338 | 6.89% |
| 300 | 4995 | 4676 | 6.82% |
| 450 | 7541 | 7014 | 7.51% |

For detail simulation results for system 5, see related tables in Appendices A and B.

### 6.2.6. System 6: Air Cooled Chillers with Fan Coil Units

In this system a packaged air cooled chiller and a chilled water pump provide chilled water to be used in local fan coils/small air handling units located throughout the building. Fan coil units have constant volume fans. Usually designers add a dedicated variable volume outdoor air unit to this system. The outdoor air unit consists of variable volume supply fan that delivers required outside air to the fan coil units through ducts and variable volume exhaust fan that relief the excess air from the building. The most important advantages of fan coil system in a large building are that if some of the fan coils break-down the whole system does not need to stop and there is no need for dedicating large interior spaces to the air handling units, but the disadvantage is they are scattered through the building and need extra piping and service.

Performance curves for each of these main components have been selected from the library of Trane Trace 700 software, two performance curves for air cooled compressors, two performance curves for supply fans, two performance curves for return fans, two performance curves for condenser fans, one performance curve for fan coil units, and one performance curves for chilled water pump. In each case family of the performance curves based on gradual increase of 0.5 or 1% tolerance from the curve default value up to the maximum allowable test tolerance based on ARI and HI standards have been generated.

Peak load condition of the equipment for the default curve on both deterministic and probabilistic calculations has been derived from the acceptable maximum power consumption from ASHRAE 90.1. (See Table 6.24 below)

Table 6.24: System 6 component efficiency@ full load condition

| **Component** | **Efficiency @ full load** | **Reference** |
|---|---|---|
| Variable Volume Fan | hp = cfm * 0.0015 | ASHRAE 90.1 2010, Table 6.5.3.1.1A |
| Constant Volume Fan (Fan Coil Units) | hp = cfm* 0.0011 | ASHRAE 90.1 2010, Table 6.5.3.1.1A |
| Air Cooled Chiller Compressor | 9.562 EER | ASHRAE 90.1 2010, Table 6.8.1C |
| Air Cooled Chiller Condenser Fan | 176000 Btuh/hp | ASHRAE 90.1 2010, Table 6.8.1G |
| Chilled Water Pump | 22 Watts/ gpm | ASHRAE 90.1 2010, Section G3.1.3.10 |

Results from sensitivity analyses in each set of simulation and also the average of all simulations have been tabulated in Table 6.25. These results show that top influential components for efficiency of the system 6 are effects of compressor and duct leak.

Table 6.25: System 6 sensitivity analysis (bin size) results (relevance of component)

| System 6 Components | Occurrence of 75% Deviation | Occurrence of 50% Deviation | Occurrence of 25% Deviation | Average Occurrence |
|---|---|---|---|---|
| Compressor | 22 | 10 | 12 | 17.4 |
| Leak | 12 | 16 | 13 | 13.3 |
| Exhaust Fan | 8 | 13 | 13 | 10 |
| Compressor age | 8 | 11 | 13 | 9.4 |
| Condenser Fan | 5 | 13 | 8 | 7.7 |
| Fan Coil Units | 5 | 10 | 5 | 6.5 |
| CHWP age | 13 | 5 | 0 | 9.3 |
| Condenser Fan age | 1 | 0 | 16 | 2.2 |
| Exhaust Fan age | 13 | 0 | 0 | 7.8 |
| Load | 1 | 7 | 3 | 3 |
| O.A. Supply Fan age | 2 | 6 | 2 | 3.2 |
| CHWP | 3 | 6 | 0 | 3.6 |
| fan Coil Units age | 2 | 1 | 6 | 2.1 |
| Coil | 2 | 0 | 6 | 1.8 |
| O.A. Supply Fan | 5 | 0 | 3 | 3.3 |

Based on the outcome of this sensitivity analysis, in another experiment, we decreased the maximum allowable tolerance of the compressor as the most influential component in this system to half of the permitted test tolerance by ARI standard. We performed multiple Monte Carlo simulations for the improved system and compared the results of the original simulation with the improved system. The simulation results show that by cutting the allowable test tolerance of the compressor by half while keeping all other components in their original values, chances that the improved system consumes less energy than lowest level of energy consumption of the original system in first year increases by 11%. Also the highest level of energy consumption of the improved system decreases by 33% compared to the energy consumption of the original system. By using this analysis, we see that by selecting the most influential component in our targeted system and pursuing the equipment manufacturer of this element to deliver an equipment that its maximum test tolerance performance is half of the allowance by the testing agencies, we could decrease the total system energy consumption by as much as 1.5% (see Table B6 in Appendix B).

Table 6.26: System 6 energy consumption comparison deterministic vs. probabilistic

| Deterministic kwh | Probabilistic kwh | % Difference | Occurrence | % Probability | % Cumulative |
|---|---|---|---|---|---|
| 3219 | | | | | |
| | 3160 | -1.83 | 0.1 | 0.02 | 0.02 |
| | 3170 | -1.52 | 0.1 | 0.02 | 0.04 |
| | 3180 | -1.21 | 11.8 | 2.36 | 2.4 |
| | 3190 | -0.90 | 3.5 | 0.7 | 3.1 |
| | 3200 | -0.59 | 2.8 | 0.56 | 3.66 |
| | 3210 | -0.28 | 26 | 5.2 | 8.86 |
| | 3220 | 0.03 | 4.6 | 0.92 | 91.14 |

Table 6.26. Continued

| | | | | | |
|---|---|---|---|---|---|
| | 3230 | 0.34 | 5.9 | 1.18 | 90.22 |
| | 3240 | 0.65 | 4.5 | 0.9 | 89.04 |
| | 3250 | 0.96 | 42.3 | 8.46 | 88.14 |
| | 3260 | 1.27 | 28.5 | 5.7 | 79.68 |
| | 3270 | 1.58 | 18.3 | 3.66 | 73.98 |
| | 3280 | 1.89 | 32.7 | 6.54 | 70.32 |
| | 3290 | 2.21 | 11.7 | 2.34 | 63.78 |
| | 3300 | 2.52 | 17.7 | 3.54 | 61.44 |
| | 3310 | 2.83 | 18.9 | 3.78 | 57.9 |
| | 3320 | 3.14 | 35.4 | 7.08 | 54.12 |
| | 3330 | 3.45 | 45 | 9 | 47.04 |
| | 3340 | 3.76 | 63 | 12.6 | 38.04 |
| | 3350 | 4.07 | 52.2 | 10.44 | 25.44 |
| | 3360 | 4.38 | 32.4 | 6.48 | 15 |
| | 3370 | 4.69 | 19.2 | 3.84 | 8.52 |
| | 3380 | 5.00 | 12.6 | 2.52 | 4.68 |
| | 3390 | 5.31 | 9 | 1.8 | 2.16 |
| | 3400 | 5.62 | 1.8 | 0.36 | 0.36 |
| | | | 500 | | |

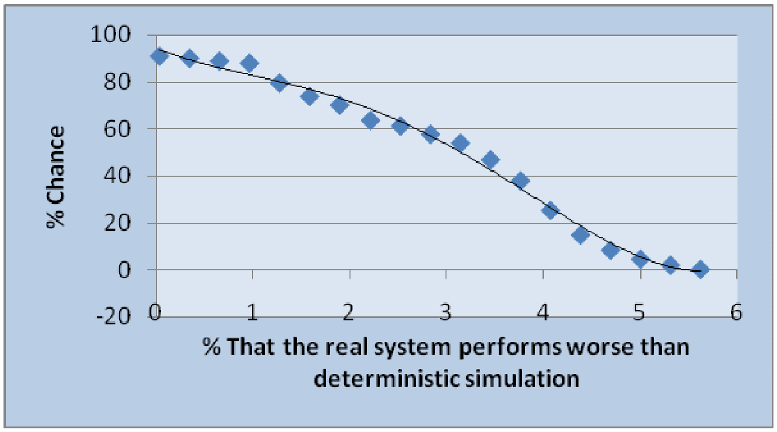


Figure 6.26: System 6 energy consumption comparison deterministic vs. probabilistic

Another outcome of this uncertainty analysis is the ability of comparison of the deterministic versus probabilistic simulations. As it is shown in Table 6.26 and Figure 6.26 we can see that e.g. there is a 15% chance that system 6 performs up to 4.38% worse than what a deterministic calculations could predict, and there is 54% chance that system 6 performs up to 3.14% worse than what a deterministic calculations could predict. The significance of this outcome will be realized when it is used as a supplemental information to the current industry energy analysis reports.

On a separate simulation we used system 6 as the base for office buildings with twice and three times larger cooling loads, and ventilation requirement and tagged the systems as 6, 6A and 6B respectively.

Table 6.27: System 6 (Office) Uncertainty

| tons | Probabilistic Mean Consumption-kwh | Deterministic kwh | System 6 Average Performance Drop |
|---|---|---|---|
| 150 | 3386.8 | 3219 | 5.21% |
| 300 | 6879.2 | 6438 | 6.85% |
| 450 | 10165.6 | 9657 | 5.27% |

For detail simulation results for system 6, see related tables in Appendices A and B.

In the following paragraphs and through the following figures, we see some more results presented through the performed analyses for all six systems and two applications that we studied.

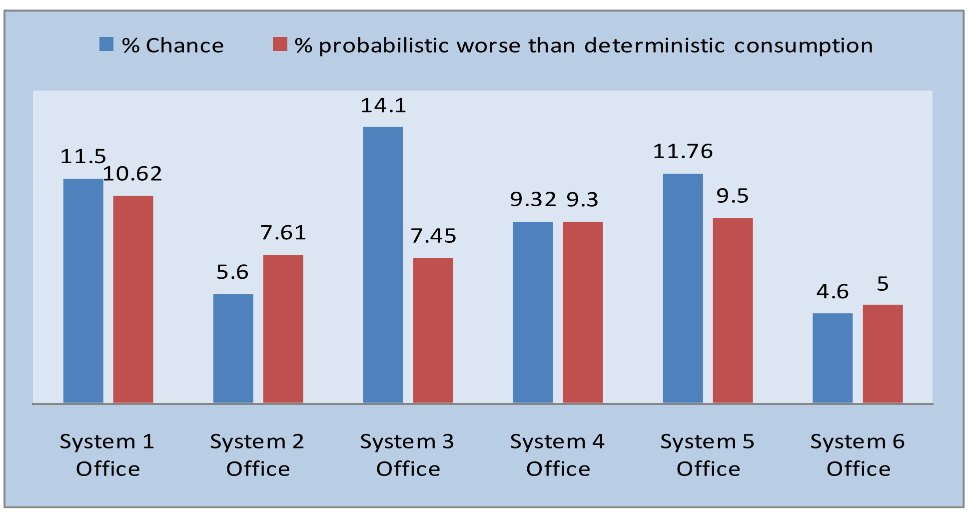


Figure 6.27: Six Office systems energy consumption comparison deterministic vs. probabilistic

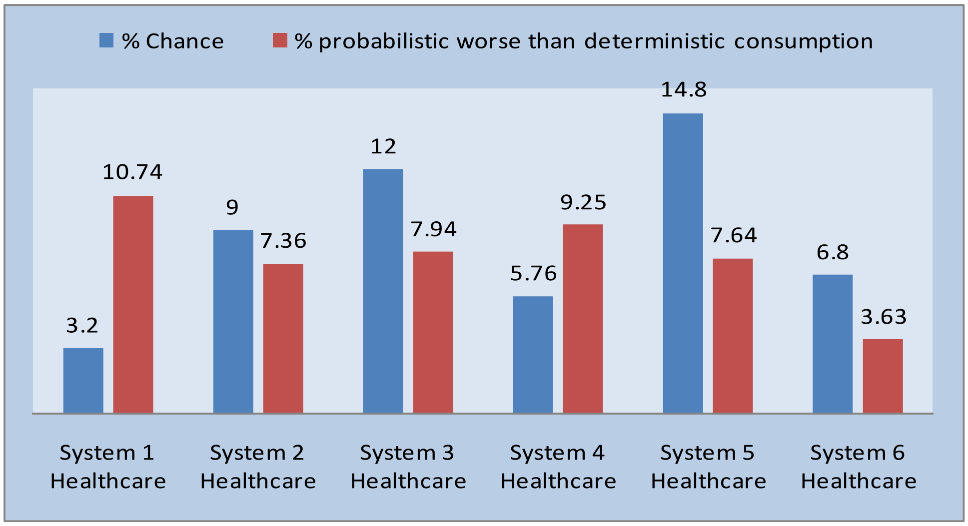


Figure 6.28: Six Healthcare systems energy consumption comparison deterministic vs. probabilistic

Table 6.28: Healthcare system 1 Uncertainty

| tons | Probabilistic Mean Consumption-kwh | Deterministic kwh | System 1 Average Performance Drop |
|---|---|---|---|
| 150 | 3279.5 | 3016 | 8.74 |
| 300 | 6557.6 | 6032 | 8.71 |
| 450 | 9851.3 | 9048 | 8.88 |

Table 6.29: Healthcare system 2 Uncertainty

| tons | Probabilistic Mean Consumption-kwh | Deterministic kwh | System 2 Average Performance Drop |
|---|---|---|---|
| 150 | 4179.6 | 3912 | 6.84 |
| 300 | 8442.1 | 7824 | 7.90 |
| 450 | 12663 | 11736 | 7.90 |

Table 6.30: Healthcare system 3 Uncertainty

| tons | Probabilistic Mean Consumption-kwh | Deterministic kwh | System 3 Average Performance Drop |
|---|---|---|---|
| 150 | 4464.8 | 4169 | 7.10 |
| 300 | 8938.1 | 8338 | 7.20 |
| 450 | 13283.6 | 12507 | 6.21 |

Table 6.31: Healthcare system 4 Uncertainty

| tons | Probabilistic Mean Consumption-kwh | Deterministic kwh | System 4 Average Performance Drop |
|---|---|---|---|
| 150 | 4231 | 3881 | 9.02 |
| 300 | 8469.3 | 7762 | 9.11 |
| 450 | 12708.9 | 11643 | 9.15 |

Table 6.32: Healthcare system 5 Uncertainty

| tons | Probabilistic Mean Consumption-kwh | Deterministic kwh | System 5 Average Performance Drop |
|---|---|---|---|
| 150 | 2706 | 2564 | 5.54 |
| 300 | 5456.6 | 5128 | 6.41 |
| 450 | 8098.4 | 7692 | 5.28 |

Table 6.33: Healthcare system 6 Uncertainty

| tons | Probabilistic Mean Consumption-kwh | Deterministic kwh | System 6 Average Performance Drop |
|---|---|---|---|
| 150 | 3646.2 | 3503 | 4.09 |
| 300 | 7290.2 | 7006 | 4.06 |
| 450 | 10939.9 | 10509 | 4.10 |

After making improvement for all the systems for both office and healthcare systems based on the results of sensitivity analyses, and collecting the results in Table 6.34 below, we can see that by improving the test tolerance for the most critical component of each system, we can reach to a level of up to 1.77% energy consumption saving.

Table 6.34: Percent improvement based on results of sensitivity analysis

| System# | Office | Healthcare |
|---|---|---|
| 1 | 1.73 | 0.13 |
| 2 | 1.25 | 0.33 |
| 3 | 0.9 | 0.73 |
| 4 | 1.77 | 0.69 |
| 5 | 0.36 | 1.14 |
| 6 | 1.55 | 1.43 |

Also for both applications we showed the difference between peak consumption of the original system versus the improved system as it shows in the Figures below.

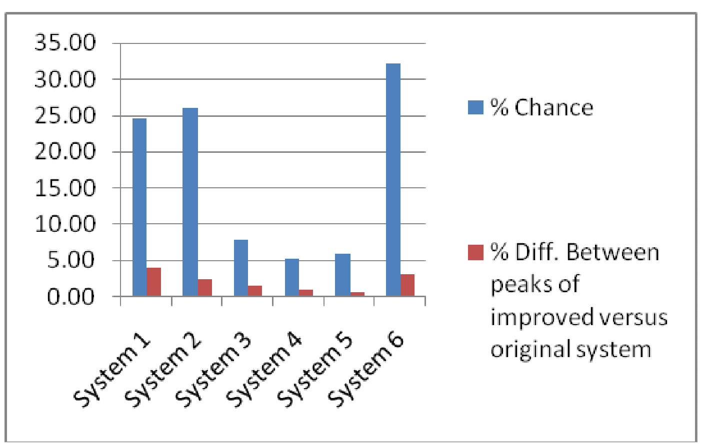


Figure 6.29: Peak consumption of the original versus improved systems (Office)

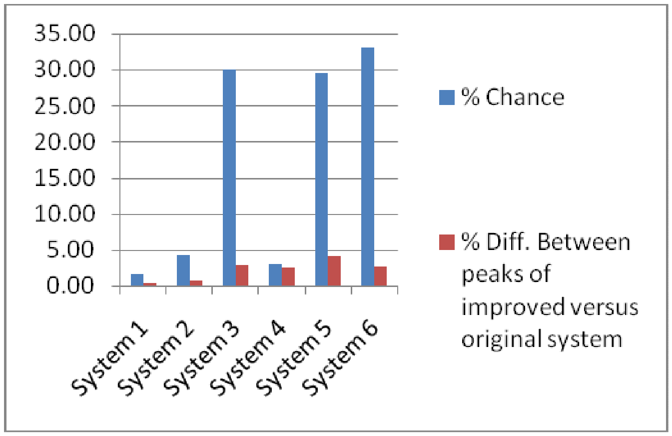


Figure 6.30: Peak consumption of the original versus improved systems (Healthcare)

Finally we have shown that pursuing the testing standard agencies to decrease the allowable test tolerance for the equipment from the current standards by 25% and 50% can translate to energy consumption of the different systems serving the same application by as much as 3.52% and 7.35% respectively. The results for all six systems that were analyzed have been tabulated in the table below:

Table 6.35: Office systems consumption improvement by decreasing the equipment test tolerance

| | 75% Mean | 50% Mean | % improvement | 25% Mean | % improvement |
|---|---|---|---|---|---|
| System 1 | 3240 | 3146 | 2.90 | 3002 | 7.35 |
| System 2 | 4143 | 3997 | 3.52 | 3868 | 6.64 |
| System 3 | 4357 | 4222 | 3.10 | 4079 | 6.38 |
| System 4 | 3999 | 3980 | 0.47 | 3769 | 5.75 |
| System 5 | 2533 | 2477 | 2.21 | 2362 | 6.75 |
| System 6 | 3442 | 3330 | 3.25 | 3226 | 6.28 |

### 6.3. BTA (Better Than Average)

In order to come up with a unique measure for comparison between all the systems available to serve the specific application we defined BTA or better than average concept (in regards with the six studied systems) in the following manner.

Table 6.36: System energy consumption comparison (Office)

| System 1 | bin | System 2 | bin | System 3 | bin | System 4 | bin | System 5 | bin | System 6 | bin | Average |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 3040 | 11.00 | 3950 | 1 | 3050 | 4 | 3880 | 1.00 | 2360 | 14.00 | 3280 | 1 | 89790 |
| 3060 | 80.00 | 3960 | 1 | 3100 | 3 | 3900 | 11.00 | 2380 | 116.00 | 3290 | 1 | 580330 |
| 3080 | 41.00 | 3970 | 2 | 4150 | 4 | 3920 | 61.00 | 2400 | 14.00 | 3300 | 18 | 482940 |
| 3100 | 46.00 | 3980 | 21 | 4250 | 390 | 3940 | 35.00 | 2420 | 85.00 | 3310 | 29 | 2323270 |
| 3120 | 66.00 | 3990 | 24 | 4300 | 99 | 3960 | 64.00 | 2440 | 44.00 | 3320 | 59 | 1284060 |
| 3140 | 5.00 | 4000 | 61 | | | 3980 | 57.00 | 2460 | 0.00 | 3330 | 75 | 736310 |
| 3160 | 21.00 | 4010 | 55 | | | 4000 | 22.00 | 2480 | 11.00 | 3340 | 105 | 752890 |
| 3180 | 31.00 | 4020 | 107 | | | 4020 | 79.00 | 2500 | 39.00 | 3350 | 87 | 1235250 |
| 3200 | 66.00 | 4030 | 59 | | | 4040 | 50.00 | 2520 | 60.00 | 3360 | 54 | 983610 |
| 3220 | 37.00 | 4040 | 86 | | | 4060 | 42.00 | 2540 | 19.00 | 3370 | 32 | 793200 |
| 3240 | 85.00 | 4050 | 36 | | | 4080 | 71.00 | 2560 | 92.00 | 3380 | 21 | 1017380 |
| 3260 | 10.00 | 4060 | 29 | | | 4100 | 7.00 | 2580 | 6.00 | 3390 | 15 | 245370 |
| 3280 | 1.00 | 4070 | 10 | | | | | | | 3400 | 3 | 54180 |
| | | 4080 | 8 | | | | | | | | | |
| | | | | | | | | | | | | 3526.19 |

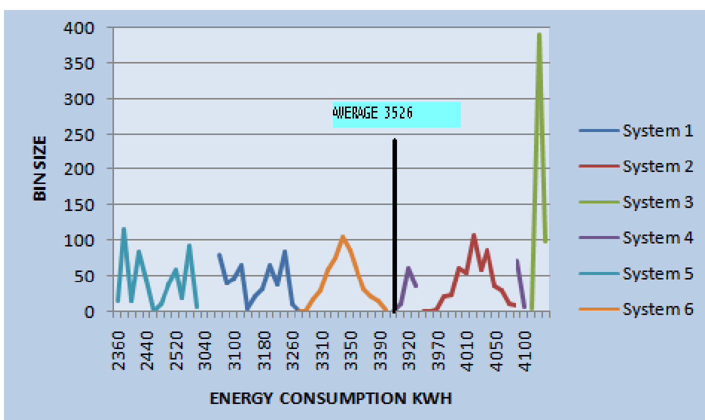


Figure 6.31: System energy consumption comparison (Office)

Results from multiple simulations for all systems (First year, 75% Mean) have been collected in Table 6.36 above. Quantity shown in lower right corner of the Table shows the average value for all these systems. Analysis of this Table can be summarized as follows:

1. System 1 performs between 100% of the times up to 7.5% ((3526-3260) x 100/3526) and 18.2% of the times up to 13.2% ((3526-3060) x 100/3526) better than the average.

2. System 2 performs between 100% of the times up to 12.87% ((3980-3526) x 100/3526) and 3.6% of the times up to 15.7% ((4080-3526) x 100/3526) worse than the average.

3. System 3 performs in 0.8% of the times up to 13.5% ((3526-3050) x 100/3050) better than the average, and performs in 20% of the times up to 21.95% ((4300-3526) x 100/3526) worse than the average, and in 99% of the times up to 18.5% ((4150-3526) x 100/3526) worse than the average.

4. System 4 performs between 100% of the times up to 10.6% ((3900-3526) x 100/3526) and 15.6% of the times up to 15.7% ((4080-3526) x 100/3526) worse than the average.

5. System 5 performs between 100% of the times up to 27.3% ((3526-2560) x 100/3526) and 26% of the times up to 32.5% ((3526-2380) x 100/3526) better than the average.

6. System 6 performs between 100% of the times up to 3.8% ((3526-3390) x 100/3526) and 3.6% of the times up to 6.9% ((3526-3280) x 100/3526) better than the average.

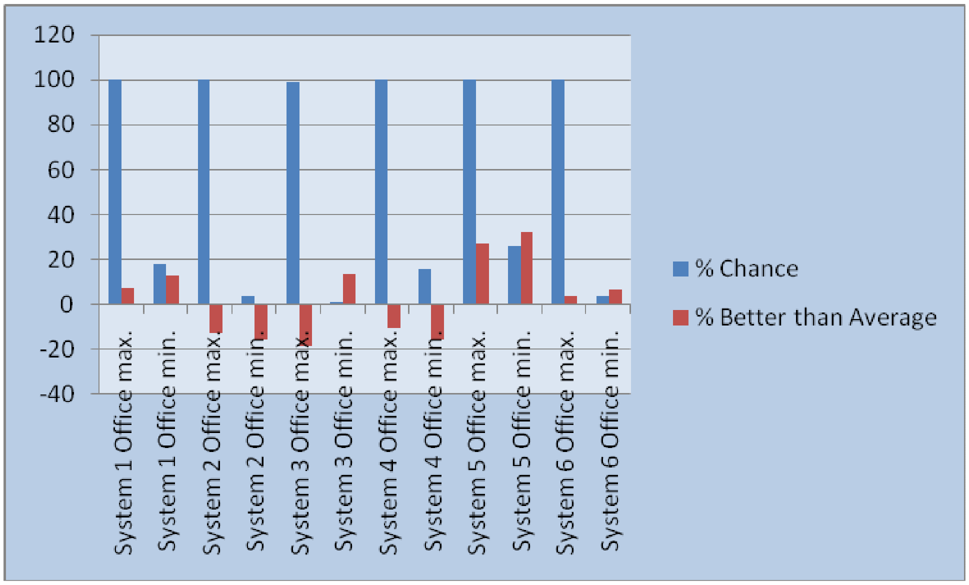


Figure 6.32: System energy consumption comparison (Office)

The results from Table 6.36 and Figures 6.31 and 6.32, have been summarized in Table 6.37 below. This table indicates that for our 150 tons Office application, system 5 has a chance of 26% to consume up to 32.5% better than average of all competitive systems. Also systems 1 and 6 respectively have chances of 18.2% and 3.6% to perform up to 13.2% and 6.9% better than average of all competitive systems respectively. Systems 4, 2 and 3 respectively have chances of 100%, 100% and 99% to perform 10.6%, 12.87% and 18.5% worse than average of all competitive systems.

Table 6.37: System energy consumption ranking (Office)

| System | % Chance | % BTA |
|---|---|---|
| Office 1 max. | 100 | 7.5 |
| Office 1 min. | 18.2 | 13.2 |
| Office 2 max. | 100 | -12.87 |
| Office 2 min. | 3.6 | -15.7 |
| Office 3 max. | 99 | -18.5 |
| Office 3 min. | 0.8 | 13.5 |
| Office 4 max. | 100 | -10.6 |
| Office 4 min. | 15.6 | -15.7 |
| Office 5 max. | 100 | 27.3 |
| Office 5 min. | 26 | 32.5 |
| Office 6 max. | 100 | 3.8 |
| Office 6 min. | 3.6 | 6.9 |

Results from multiple simulations for all Healthcare systems (First year, 75% Mean) have been collected in Table 38 below. Quantity shown in lower right corner of the Table shows the average value for all these systems. Analysis of this Table can be summarized as follows:

Table 6.38: System energy consumption comparison (Healthcare)

| System 1 | bin | System 2 | bin | System 3 | bin | System 4 | bin | System 5 | bin | System 6 | bin | Average |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 3100 | 2.00 | 4100 | 1.00 | 3100 | 10.00 | 4040 | 19.00 | 2560 | 30.00 | 3540 | 4.00 | 209020 |
| 3120 | 8.00 | 4110 | 4.00 | 4300 | 10.00 | 4060 | 38.00 | 2580 | 91.00 | 3550 | 5.00 | 491210 |
| 3140 | 70.00 | 4120 | 16.00 | 4400 | 380.00 | 4080 | 44.00 | 2600 | 17.00 | 3560 | 37.00 | 2313160 |
| 3160 | 51.00 | 4130 | 18.00 | 4500 | 100.00 | 4100 | 17.00 | 2620 | 62.00 | 3570 | 57.00 | 1121130 |
| 3180 | 26.00 | 4140 | 68.00 | | | 4120 | 66.00 | 2640 | 59.00 | 3580 | 16.00 | 849160 |
| 3200 | 69.00 | 4150 | 45.00 | | | 4140 | 35.00 | 2660 | 0.00 | 3590 | 111.00 | 950940 |
| 3220 | 16.00 | 4160 | 99.00 | | | 4160 | 52.00 | 2680 | 3.00 | 3600 | 106.00 | 1069320 |
| 3240 | 1.00 | 4170 | 45.00 | | | 4180 | 65.00 | 2700 | 15.00 | 3610 | 48.00 | 676370 |
| 3260 | 46.00 | 4180 | 89.00 | | | 4200 | 60.00 | 2720 | 81.00 | 3620 | 59.00 | 1207880 |
| 3280 | 39.00 | 4190 | 40.00 | | | 4220 | 56.00 | 2740 | 18.00 | 3630 | 42.00 | 733620 |
| 3300 | 60.00 | 4200 | 47.00 | | | 4240 | 46.00 | 2760 | 88.00 | 3640 | 3.00 | 844240 |
| 3320 | 32.00 | 4210 | 22.00 | | | 4260 | 2.00 | 2780 | 36.00 | 3650 | 12.00 | 351260 |
| 3340 | 57.00 | 4220 | 4.00 | | | | | | | | | 207260 |
| 3360 | 23.00 | 4230 | 2.00 | | | | | | | | | 85740 |
| | | | | | | | | | | | | |
| | | | | | | | | | | | | 3703.44 |

1. System 1 performs between 100% of the times up to 9.2% ((3703-3360) x 100/3703) and 16% of the times up to 15.2% ((3703-3140) x 100/3703) better than the average.

2. System 2 performs between 100% of the times up to 10.7% ((4100-3703) x 100/3703) and 5.6% of the times up to 13.6% ((4210-3703) x 100/3703) worse than the average.

3. System 3 performs in 2% of the times up to 16.2% ((3703-3100) x 100/3703) better than the average, and performs in 20% of the times up to 21.5% ((4500-3703) x 100/3703) worse than the average, and in 98% time up to 10% ((4300-3703) x 100/3703) worse than average.

4. System 4 performs between 100% of the times up to 9.1% ((4040-3703) x 100/3703) and 9.6% of the times up to 14.5% ((4240-3703) x 100/3703) worse than the average.

5. System 5 performs between 100% of the times up to 24.9% ((3703-2780) x 100/3703) and 24.2% of the times up to 30% ((3703-2580) x 100/3703) better than the average.

6. System 6 performs between 100% of the times up to 1.4% ((3703-3650) x 100/3703) and 9.2% of the times up to 3.8% ((3703-3560) x 100/3703) better than the average.

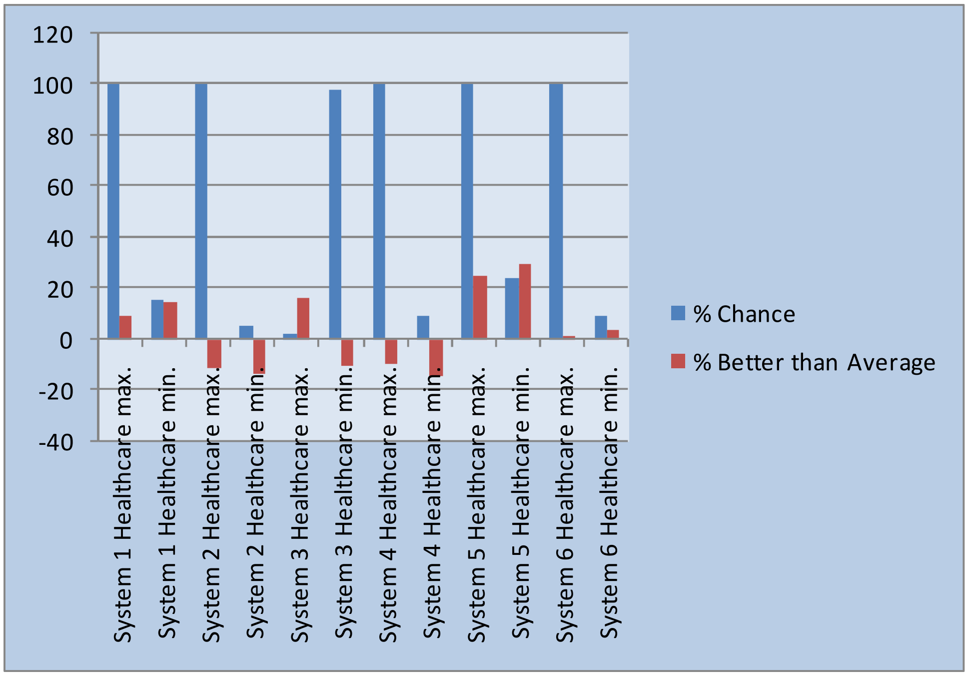


Figure 6.33: System energy consumption comparison (Healthcare)

The results from Table 6.38 and Figure 6.33, have been summarized in Table 6.39 below. This table indicates that for our 150 tons Healthcare application, system 5 has a chance of 24.2% to consume up to 30% better than average of all competitive systems. Also systems 1 and 6 respectively have chances of 16% and 3.9% to perform up to 15.2% and 3.8% better than average of all competitive systems respectively. Systems 2, 3 and 4 respectively have 100%, 98% and 100% chance to perform 10.7%, 10% and 9.1% worse than average of all competitive systems.

Table 6.39: System energy consumption ranking (Healthcare)

| System | % Chance | % BTA |
|---|---|---|
| Healthcare 1 max. | 100 | 9.2 |
| Healthcare 1 min. | 16 | 15.2 |
| Healthcare 2 max. | 100 | -10.7 |
| Healthcare 2 min. | 5.6 | -13.6 |
| Healthcare 3 max. | 2 | 16.2 |
| Healthcare 3 min. | 98 | -10 |
| Healthcare 4 max. | 100 | -9.1 |
| Healthcare 4 min. | 9.6 | -14.5 |
| Healthcare 5 max. | 100 | 24.9 |
| Healthcare 5 min. | 24.2 | 30 |
| Healthcare 6 max. | 100 | 1.4 |
| Healthcare 6 min. | 9.2 | 3.8 |

## 6.4. Summary

We made the following assumptions:

1. Equipments are being built with some allowable degree of tolerance.

2. These tolerances cause uncertainty in performance of the equipment.

3. Uncertainty in performance of the equipment can be quantified.

4. These quantified uncertainties can help in:

- Selecting the most efficient system for an application.

- Preventing systems from scoring efficiency labels that they are not really performing up to required levels.

- Developing a risk based language that gives a comparison label to any system in comparison to the average consumption of all other applicable systems for the same application.

and we set up the framework as follows:

The plan here was to establish a systematic approach of developing expressions of risk and reliability in commercial cooling system consumption and efficiency calculations, and thus advocate the use of expressions of risk as design targets.

In order to develop the risk expressions, we selected six most popular systems that are usually being used to provide cooling for the office buildings and healthcare facilities and performed multiple Monte Carlo simulation for each system to calculated the energy consumption of the system in a detail form with energy consumption intervals and also the bin size registered for each interval.

These results have been collected in tables such as Table B7, Appendix B. Of course other systems can be utilized for the targeted application, but it would have made this process very exhaustive and also it would not have added any additional value to the research due to unrealistic chance of utilization of such systems in the real world.

The method was to calculate the average energy consumption of all these six systems and establish that as the base measure for allocating risk to all the systems compare to that average value. We called this measure BTA or better than average. As it is shown in Table B7, for each system all the energy consumption values less than this average and the bin size registered for them represent the chances of that specific system to perform better than average and all the energy consumption values more than this average and the bin size registered for them represent the chances of that specific system to perform worse than average. The expression of risk in these conditions would be "there is x% (percent of registered bin to total bin size) chance that system "A" performs y% (percent difference between the registered consumption to the average consumption) better than average" and "there is z% chance that system "A" performs w% worse than average".

And by performing the simulations and analyses in this chapter we have confirmed:

1. As the system size changes the most influential parameter of the system changes as well.
2. For the possible systems serving a specific application and a certain size a better than average (BTA) value can be generated that can be used as an effective risk based tool in selecting the proper system with desired level of energy efficiency and consumption among the different systems that can be utilized for that application. It has been shown that this method can help selecting systems that have 100% chances to perform up to 24% better than average.
3. The current energy efficiency evaluation can be improved by using risk based analysis. We have shown that using this method for a mid size office building can be translated to a chance of 11.5% for up to 10.6% energy savings, only by changing the current mind-set of acting as if the energy performance of an uncertain system can be calculated deterministically.
4. We have shown that using sensitivity analysis can provide insight to the operation of the systems that then can help to improve the energy efficiency and consumption of the system. We have shown for a mid-size office building this energy consumption saving could be as high as 1.77%.

5. It also has been shown that when improving the system based on the results of the sensitivity analysis, there is up to a 25% chance that the maximum energy consumption of the original system be up to 3.5% higher than maximum energy consumption of the improved system. This could be a crucial cost issue, since most of the utility providers, set the base charging price of the electricity for a building based on the maximum usage (peak) of the electricity.

6. We also have shown that pursuing the testing standard agencies to decrease the allowable test tolerance for the equipment from the current standards by 25% and 50% can translate to lower energy consumption of the different systems serving the same application by as much as 3.52% and 7.55% respectively.

As it can be seen, in the level of system comparison against other systems, we have shown that it is possible to use sentences such as "By selecting system “A” versus other systems that are also suitable for our specific application, there is up to 100% chance that system “A” performs up to 14% better than average (e.g. system 1, office buildings). This can be separated to two sub-statements as follows: (1) there is 1.4% chance that system “A” performs up to 13% better, and (2) there is 98.4% chance that system “A” performs up to 21% worse than average (e.g. system 3, office buildings)"

In other word for the systems (for Office building) that we analyzed we can say:

1. System 1 performs between 100% of the times up to 7.5% ((3526-3260) x 100/3526) and 18.2% of the times up to 13.2% ((3526-3060) x 100/3526) better than the average.

2. System 2 performs between 100% of the times up to 12.87% ((3980-3526) x 100/3526) and 3.6% of the times up to 15.7% ((4080-3526) x 100/3526) worse than the average.

3. System 3 performs in 0.8% of the times up to 13.5% ((3526-3050) x 100/3050) better than the average, and performs in 20% of the times up to 21.95% ((4300-3526) x 100/3526) worse than the average, and in 99% of the time up to 18.5% ((4150-3526) x 100/3526) worse than the average.

4. System 4 performs between 100% of the times up to 10.6% ((3900-3526) x 100/3526) and 15.6% of the times up to 15.7% ((4080-3526) x 100/3526) worse than the average.

5. System 5 performs between 100% of the times up to 27.3% ((3526-2560) x 100/3526) and 26% of the times up to 32.5% ((3526-2380) x 100/3526) better than the average.

6. System 6 performs between 100% of the times up to 3.8% ((3526-3390) x 100/3526) and 3.6% of the times up to 6.9% ((3526-3280) x 100/3526) better than the average.

And for healthcare systems we can say:

1. System 1 performs between 100% of the times up to 9.2% ((3703-3360) x 100/3703) and 16% of the times up to 15.2% ((3703-3140) x 100/3703) better than the average.

2. System 2 performs between 100% of the times up to 10.7% ((4100-3703) x 100/3703) and 5.6% of the times up to 13.6% ((4210-3703) x 100/3703) worse than the average.

3. System 3 performs in 2% of the times up to 16.2% ((3703-3100) x 100/3703) better than the average, and performs in 20% of the times up to 21.5% ((4500-3703) x 100/3703) worse than the average, and in 98% time up to 10% ((4300-3703) x 100/3703) worse than average.

4. System 4 performs between 100% of the times up to 9.1% ((4040-3703) x 100/3703) and 9.6% of the times up to 14.5% ((4240-3703) x 100/3703) worse than the average.

5. System 5 performs between 100% of the times up to 24.9% ((3703-2780) x 100/3703) and 24.2% of the times up to 30% ((3703-2580) x 100/3703) better than the average.

6. System 6 performs between 100% of the times up to 1.4% ((3703-3650) x 100/3703) and 9.2% of the times up to 3.8% ((3703-3560) x 100/3703) better than the average.

Finally in the level of system comparison against itself, we have shown that it is possible to use sentences such as "Due to the existence of unknown factors (e.g. equipment test tolerance allowances) there is a chance (e.g. 32% in case of system 3, office buildings) that the system “A” performs up to 8.7% worse than what a deterministic calculations can predict. This statement can be presented in an incremental form also, so we can state: (1) there is up to 32% chance that system “A” can perform up to 8.7% worse that what a deterministic calculations can predict, (2) there is up to 66.6% chance that system “A” can perform up to 2.95% worse that what a deterministic calculations can predict, (3) .... etc."

Basically we have shown that for the following systems, effects of equipment test allowance can cause up to the shown percentage extra overall energy consumption over the results achieved by the traditional calculations:

Office Building, System 1; there is 11.5% chance that the actual system uses up to 10.6% extra energy compare to what a traditional simulation can predict.

Office Building, System 2; there is 5.6% chance that the actual system uses up to 7.6% extra energy compare to what a traditional simulation can predict.

Office Building, System 3; there is 14.1% chance that the actual system uses up to 7.45% extra energy compare to what a traditional simulation can predict.

Office Building, System 4; there is 9.3% chance that the actual system uses up to 9.3% extra energy compare to what a traditional simulation can predict.

Office Building, System 5; there is 11.76% chance that the actual system uses up to 9.5% extra energy compare to what a traditional simulation can predict.

Office Building, System 6; there is 4.6% chance that the actual system uses up to 5% extra energy compare to what a traditional simulation can predict.

Healthcare Building, System 1; there is 3.2% chance that the actual system uses up to 10.7% extra energy compare to what a traditional simulation can predict.

Healthcare Building, System 2; there is 9% chance that the actual system uses up to 7.36% extra energy compare to what a traditional simulation can predict.

Healthcare Building, System 3; there is 12% chance that the actual system uses up to 7.94% extra energy compare to what a traditional simulation can predict.

Healthcare Building, System 4; there is 5.7% chance that the actual system uses up to 9.2% extra energy compare to what a traditional simulation can predict.

Healthcare Building, System 5; there is 14.8% chance that the actual system uses up to 7.64% extra energy compare to what a traditional simulation can predict.

Healthcare Building, System 6; there is 6.8% chance that the actual system uses up to 3.63% extra energy compare to what a traditional simulation can predict.

We have also shown that for the following systems, improving the effects of the most important equipment test allowance (cutting the most influential equipment test allowance in half) can cause up to the shown percentage overall energy consumption savings over the results achieved by the probabilistically calculations without equipment test allowance improvement:

Office Building, System 1; there is a chance of up to 1.73% overall energy consumption saving.

Office Building, System 2; there is a chance of up to 1.25% overall energy consumption saving.

Office Building, System 3; there is a chance of up to 0.9% overall energy consumption saving.

Office Building, System 4; there is a chance of up to 1.77% overall energy consumption saving.

Office Building, System 5; there is a chance of up to 0.36% overall energy consumption saving.

Office Building, System 6; there is a chance of up to 1.55% overall energy consumption saving.

Healthcare Building, System 1; there is a chance of up to 0.13% overall energy consumption saving.

Healthcare Building, System 2; there is a chance of up to 0.33% overall energy consumption saving.

Healthcare Building, System 3; there is a chance of up to 0.73% overall energy consumption saving.

Healthcare Building, System 4; there is a chance of up to 0.69% overall energy consumption saving.

Healthcare Building, System 5; there is a chance of up to 1.14% overall energy consumption saving

Healthcare Building, System 6; there is a chance of up to 1.43% overall energy consumption saving.

We have also shown that for the following systems, improving the effects of the most important equipment test allowance (cutting the most influential equipment test allowance in half) can cause the shown percent chance that the maximum energy consumption of the original system be up to shown percent higher than maximum energy consumption of the improved system. This could be a crucial cost issue, since most of the utility providers, set the base charging price of the electricity for a building based on the maximum usage (peak) of the electricity.

Office Building, System 1; 25% chance that maximum energy consumption of original system be up to 4.2% higher than maximum energy consumption of the improved system.
Office Building, System 2; 26% chance that maximum energy consumption of original system be up to 2.5% higher than maximum energy consumption of the improved system.
Office Building, System 3; 7.8% chance that maximum energy consumption of original system be up to 1.6% higher than maximum energy consumption of the improved system.
Office Building, System 4; 5.2% chance that maximum energy consumption of original system be up to 0.9% higher than maximum energy consumption of the improved system.
Office Building, System 5; 5.7% chance that maximum energy consumption of original system be up to 1.5% higher than maximum energy consumption of the improved system.
Office Building, System 6; 32% chance that maximum energy consumption of original system be up to 3.3% higher than maximum energy consumption of the improved system.

Healthcare Building, System 1; 1.1% chance that maximum energy consumption of original system be up to 0.6% higher than maximum energy consumption of the improved system.
Healthcare Building, System 2; 4.3% chance that maximum energy consumption of original system be up to 0.7% higher than maximum energy consumption of the improved system.
Healthcare Building, System 3; 30% chance that maximum energy consumption of original system be up to 3.2% higher than maximum energy consumption of the improved system.
Healthcare Building, System 4; 2.9% chance that maximum energy consumption of original system be up to 0.2% higher than maximum energy consumption of the improved system. Healthcare Building, System 5; 29.6% chance that maximum energy consumption of original system be up to 4.1% higher than maximum energy consumption of the improved system.
Healthcare Building, System 6; 25.9% chance that maximum energy consumption of original system be up to 2.5% higher than maximum energy consumption of the improved system.

we also derived values that are representatives of the differences between the energy consumption calculated in a deterministic way versus the one calculated in a probabilistic (both in detail range and mean value of the distribution) way at that capacity, or "the system uncertainty at that specific capacity".

## 6.5. After Thoughts

Based on the data from the Building Energy Data Book 2010 (D and R International, Ltd 2011) total commercial building floor space area in year 2010 and expected total commercial building floor space area in year 2035 are $81.2*10^9$ $ft^2$ and $109.8*10^9$ $ft^2$ respectively. The same reference also shows the share of cooling and ventilating systems energy intensity for office buildings which make up 17% of total commercial spaces are 14100 $btu/ft^2$, and the share of cooling systems energy intensity for healthcare buildings which make up 4% of total commercial spaces are 27400 $btu/ft^2$. (See Tables 3.2.1, 3.2.2 and 3.2.13 in the Building Energy Data Book 2010 (D and R International, Ltd 2011) Under two different scenarios (1) counting only the expected new constructions from year 2010 to year 2035 (total of $27.6*10^9$ $ft^2$ new floor space for commercial buildings) and (2) using the total expected commercial buildings in year 2035 (total of $109*10^9$ $ft^2$ floor space for commercial buildings) based on the industry-wide acceptable assumption that expected life of most of the HVAC equipments are about 25 years or less, and therefore all the HVAC systems in the current commercial buildings (in our research office and healthcare buildings) would be replaced during the next 25 years, we can present the amount of potential energy savings expected by proposed methods in this thesis can be translated to about $1.03*10^{11}$ btu by 2015 and up to $1.51*10^{11}$ btu by 2035 for office buildings and about $0.47*10^{11}$ btu by 2015 and up to $0.69*10^{11}$ btu for healthcare buildings per year per every 1% improvement for the scenario1 (See Table 28 below), and about 6.85*$10^{11}$ btu for office buildings and 3.13*$10^{11}$ btu for healthcare buildings per year per every 1% improvement for the scenario 2, starting year 2035.

Table 6.40: Predicted energy saving thru 2035

| Commercial sector Floor Space-10^9 ft2 | % Office | % Healthcare | Total Office Space-10^9 ft2 | Total Healthcare Space-10^9 ft2 | New Office 10^9 ft2 | New Healthcare 10^9 ft2 |
|---|---|---|---|---|---|---|
| | | | | | | |
| 81.2 | 17 | 4 | 13.804 | 3.248 | - | - |
| 85.5 | 17 | 4 | 14.535 | 3.42 | 0.731 | 0.172 |
| 91.5 | 17 | 4 | 15.555 | 3.66 | 1.02 | 0.24 |
| 97.4 | 17 | 4 | 16.558 | 3.896 | 1.003 | 0.236 |
| 103.5 | 17 | 4 | 17.595 | 4.14 | 1.037 | 0.244 |
| 109.8 | 17 | 4 | 18.666 | 4.392 | 1.071 | 0.252 |
| Office Intensity btu/ft2 | Healthcare Intensity btu/ft2 | Total consumption Office-btu 10^9 | Total Consumption Healthcare-btu 10^9 | Accumulative Total consumption Office-btu 10^9 | Accumulative Total Consumption Healthcare-btu 10^9 | |
| | | | | | | |
| - | - | - | - | | | |
| 14100 | 27400 | 10307.1 | 4712.8 | 10307.1 | 4712.8 | |
| 14100 | 27400 | 14382 | 6576 | 24689.1 | 11288.8 | |
| 14100 | 27400 | 14142.3 | 6466.4 | 38831.4 | 17755.2 | |
| 14100 | 27400 | 14621.7 | 6685.6 | 53453.1 | 24440.8 | |
| 14100 | 27400 | 15101.1 | 6904.8 | 68554.2 | 31345.6 | |

# CHAPTER 7

# EFFECTS OF SENSOR ERROR

Malfunctioning of equipments and controls in HVAC systems have been proved to be one of the sources of wasted energy in HVAC systems. Commissioning agents have been spending a large amount of time to find and replace the malfunctioning items as soon as possible. The expectation is that this can cut the quantity of the wasted energy considerably.

A group of researchers (Basarkar et al. 2011) identified a number of common HVAC equipment faults and developed a detail fault model in EnergyPlus. They showed that the presence of HVAC faults can influence total HVAC energy use by as much as 22%.

In this chapter we will show the results of simulations in order to investigate the effects of malfunctioning temperature sensors on the overall energy consumption of systems.

Up to this point all simulations were based on the assumption that there is no uncertainty in the sensed temperature and humidity of the air at the designated locations. These locations are typically outdoor, room and leaving cooling coil temperature and humidity sensors.

In real life applications there is always a chance that one or some of these sensors (in this research one or some of the temperature sensors) perform with anomaly. That means there is a possibility that one or some sensors is (are) broken and continuously show temperatures that are different from the real outside, room or coil leaving temperatures. Therefore the sensor readings can cause miscalculations by the control system and as a result the system will be forced to either over-cool or under-cool the space, depending on the high or low readings of the erroneous temperature sensors.

For The purpose of our simulation we make the assumption that one or some of the main temperature sensors (outdoor, room and cold air supply) could continuously show temperature of up to 2 degree F higher than what it is supposed to show. It means e.g. the temperature sensor that represents the room temperature and by design it is set to keep the room in 75 degrees F, continuously shows 75 degrees F, while the real room temperature is somewhere between 75 to 77 degrees F, By the same token the temperature sensor that represents the outdoor temperature continuously shows between 0 to 2 degrees higher than what the real outdoor temperature is.

In order to include the effects of these broken temperature sensors we selected system type 1 and used the calculation platform after revising the inputs in a way that in addition to all the parameters previously introduces, these are three additional ones, i.e. three local temperature sensors that carry on uncertainty in the range between 0 and 2 F.

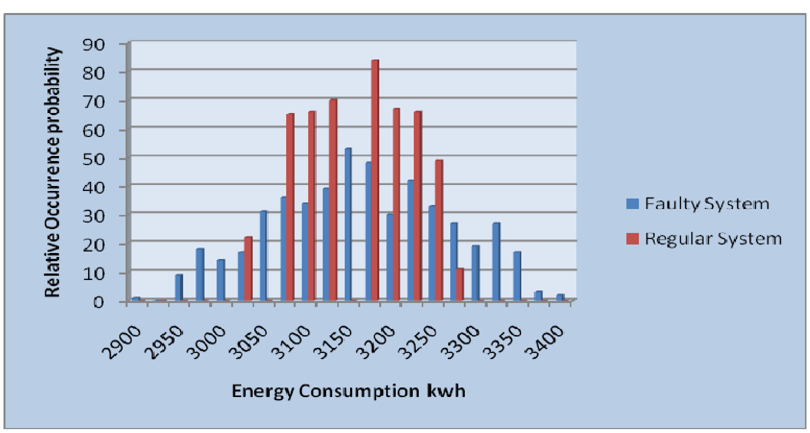


Figure 7.1: System 1 effects of faulty sensors on energy consumption

The simulation containing uncertainty outcome shows near 0.3% increase in total consumption, and up to 13% chance that the peak consumption of a system with malfunctioning sensor will be up to 0.3% higher than the peak consumption of the original system. The outcome of a sensitivity analysis on this system also shows that the temperature sensor located at the leaving cold air location has the most influence on increasing the level of uncertainty on energy consumption of the whole system. The room temperature sensor has a relatively high influence, whereas the outdoor air temperature sensor is not as important as the other two sensors (see Table 7.1, below). The reason for this phenomenon can be explained in this way that in the load calculations outdoor temperature multiplies by the outdoor flow capacity (usually responsible for 20-30% of the total air that requires to be cooled), room temperature multiplies by the return air flow capacity (usually 70-80% of the total air that requires to be cooled) and the cooling coil leaving temperature multiplies by the 100% of the air that requires to be cooled.

Table 7.1: System 1 Original versus Faulty sensor energy consumption

| Consumption Level kwh | Original System bin | Faulty System bin | Original Consumption kwh | Faulty Consumption kwh | Net Consumption change % |
|---|---|---|---|---|---|
| 2900 | | 1 | 0 | 2900 | |
| 2950 | | 27 | 0 | 79650 | |
| 3000 | | 31 | 0 | 93000 | |
| 3040 | 22 | | 66880 | 0 | |
| 3050 | | 67 | 0 | 204350 | |
| 3060 | 80 | | 244800 | 0 | |
| 3080 | 41 | | 126280 | 0 | |
| 3100 | 83 | 73 | 257300 | 226300 | |

Table 7.1. Continued

| | | | | | |
|---|---|---|---|---|---|
| 3120 | 27 | | 84240 | 0 | |
| 3140 | 5 | | 15700 | 0 | |
| 3150 | | 100 | 0 | 315000 | |
| 3160 | 21 | | 66360 | 0 | |
| 3180 | 75 | | 238500 | 0 | |
| 3200 | 32 | 72 | 102400 | 230400 | |
| 3220 | 37 | | 119140 | 0 | |
| 3240 | 66 | | 213840 | 0 | |
| 3250 | | 60 | 0 | 195000 | |
| 3260 | 10 | | 32600 | 0 | |
| 3280 | 1 | | 3280 | 0 | |
| 3300 | | 46 | 0 | 151800 | |
| 3350 | | 18 | 0 | 60300 | |
| 3400 | | 5 | 0 | 17000 | |
| | | | 1571320 | 1575700 | 0.28 |

Table 7.2: System 1 sensitivity analysis results (relevance of component), Sensors included

| Item | 75% | 50% | 25% | Average |
|---|---|---|---|---|
| Supply Temp. | 10 | 8 | 5 | 8.9 |
| Supply Fan | 5 | 3 | 3 | 4.2 |
| Cooling Tower | 4 | 6 | 1 | 4.3 |
| CWP | 2 | 1 | 1 | 1.6 |
| Supply Fan Age | 1 | 1 | 7 | 1.6 |
| CWP age | 3 | 5 | 5 | 3.8 |
| Room Temp. | 7 | 5 | 12 | 6.9 |
| Outdoor Temp. | 4 | 1 | 2 | 2.9 |
| Cooling Tower age | 3 | 7 | 3 | 4.2 |
| Coil | 1 | 5 | 4 | 2.5 |
| TU | 4 | 7 | 1 | 4.6 |
| Return Fan age | 11 | 5 | 2 | 8.3 |
| Chiller age | 6 | 12 | 3 | 7.5 |
| CHWP | 2 | 4 | 6 | 3 |

Table 7.2. Continued

| | | | | |
|---|---|---|---|---|
| TU age | 10 | 5 | 11 | 8.6 |
| Leak | 8 | 1 | 7 | 5.8 |
| CHWP age | 2 | 5 | 7 | 3.4 |
| Chiller | 1 | 6 | 9 | 3.3 |
| Return Fan | 11 | 1 | 5 | 7.4 |
| Load | 5 | 10 | 1 | 6.1 |

The results of this simulation validates the importance of the degree of accuracy of the temperature sensors, specifically for the cold air leaving the cooling coil, and the room temperature sensors, and emphasizes that it could be a contributor to total system energy savings and efficiency improvement. But at the same time shows the effects of these sensors are not nearly as important as the effects of equipment test tolerance as has been targeted throughout this research. Of course further simulations and researches may prove a higher degree of importance for these sensors in certain conditions and for certain system types. This will be a topic for future investigation.

# CHAPTER 8

# USE IN WHOLE BUILDING SIMULATION

Current whole building simulation models do not accurately predict the combined effect of the many uncertainties affecting the efficiency of the wide variety of interacting systems in buildings.

In the parallel NSF-EFRI sponsored project mentioned before, a research team is looking to address this issue. Their emphasis has been on quantifying uncertainties on the building demand side, for the time being ignoring systems, and focusing on the effects of uncertain parameters that contribute to the dynamic cooling (or heating) load simulation in the building. These parameters relate to heat transfer characteristics of the construction materials ( shading coefficient of the glasses, U-values of the walls, occupancy variability, etc. ).

This thesis complements the NSF-EFRI work in the sense that it may provide the ideal way to take HVAC system uncertainties into account when translating the load (distribution) into energy consumption and cost (distribution). But there are several open questions as how the two efforts can be connected in an effective way. For better understanding of these questions and challenges let’s first discuss the nature of whole building energy models and the interaction between the HVAC system and the building assumed and represented in current building energy simulation tools.

Building energy models use heat and mass balance equations, temperature set point schedules, operational schedules and psychrometric equations to calculate total sensible and total latent loads for all zones and the building as a whole for each hour of the year. The NSF-EFRI team is extending these energy models with uncertainty ranges of all relevant parameters in the model, not only in the model of the building physical behavior but also in occupant uncertainty, workmanship, scheduling and control uncertainty, and of course uncertainty in the HVAC system parameters. If the simulation tool is able to handle the whole building including the dynamic interaction between the building and the systems, the natural step is to perform the full uncertainty analysis with the whole building simulation model. An intriguing question is however, whether such a brute force approach to the combined demand and supply uncertainty is necessary given the fact that the combined simulation is computationally intensive and, perhaps more important, requires a substantial effort on the part of the modeler as the systems part of a building energy model is requires a high level of expertise and attention to modeling details.

This approach would also call for a deep extension of the system part of the simulation software as the embedded performance curves will have to be parameterized in the same way as described in this thesis, in order to enter the uncertainty tolerances of the different components that make up the system specification.

The research reported here may supply a better approach. Indeed, if the building energy simulation stops at the generation of the load (hourly values with an uncertainty distribution) this load could indeed be used as input to the calculations of the previous chapter. These calculations would then “add” the effect of system tolerances and compute the combined effect of load and system uncertainties. Obviously, in this way both calculations would be performed without interaction, whereas we realize that in fact the building dynamics and system dynamics are in "dynamically" interacting. This interaction can be strong or weak depending on the type of the combination of buildings and systems. It is clear that the neglect of the dynamic interaction will introduce an error in the sequential approach, which could be introduced as just another source of uncertainty in the energy consumption outcomes. Another, more pedestrian aspect of the suggested approach is the use of the day by day active propagation through the system calculation routines presented in this thesis, or the use of the average system efficiency (distribution) as a multiplier of the calculated loads. The latter will obviously yet introduce another error, originating from the fact that we assume that monthly totals could be simply multiplied by an average monthly efficiency.

The next stage of the work will perform a range of experiments to decide which approach is acceptable in which circumstances. The different approaches considered will be:

- Fully integrated dynamic demand and supply (system) simulation
- Weakly integrated demand simulation with system simulation performed as add on step (based on hourly, daily or monthly averaged load information)
- Non-integrated simulation where no system simulation is performed, but rather average system efficiency data (generated in this thesis) is used as multiplier to deliver system consumption outcomes.

The data of the experiments with each approach will be used to quantify the error introduced in the second and third approach, relative to the fully integrated approach. A sensitivity study will reveal in which case the error is unacceptable for a given decision contexts which would thus automatically require a brute force uncertainty analysis, i.e. based on fully integrated dynamic simulation.

# CHAPTER 9

# CONCLUSION AND FUTURE WORK

This thesis makes a contribution to improving our fundamental understanding of variability of performance of HVAC systems as a result of component performance tolerances. This has led to the quantification of risk in decisions related to the selection and sizing of six mainstream HVAC cooling system design concepts. The main outcomes of the thesis can be enumerated in the following findings.

1. This research showed that choosing between different candidate systems for a specific application utilizing a probabilistic method, can be based on expression of risk of the following form: " there is X% chance to reduce the overall energy consumption by as much as Y%, by selecting a specific system over another system for a specific application". Chapter 6 lists the findings for the 6 mainstream systems if applied in office buildings and hospitals.
2. This research also showed that with introduction of a probabilistic analysis in the current state of energy modeling, the chances that a real building performs worse than what a deterministic simulation can predict can be represented in a performance risk format such as "there is X% chance that the real system performs Y% worse than what a deterministic simulation can predict". Chapter 6 lists the findings for 6 mainstream systems if applied in office buildings and hospitals.

3. The research showed that reducing the performance deviation from the current maximum allowable levels for the most influential components in the system can be translated to an average reduction of the overall energy consumption of the considered system by as much as 1.77%. This finding is important in the pending discussions of how a decrease in allowable manufacturing tolerances might not only reduce the uncertainty in the energy cost expectations, but in fact improve the average energy performance by almost 2%. It is expected that testing agencies and code officials will pay more attention to this trade-off between stricter tolerance testing and across the board energy savings.

Suggested future work based on the outcome of this thesis are (1) performing same type analysis for different type applications (e.g. educational or laboratory facilities) and wider range of system capacities (i.e. very small or very large facilities), (2) creating a commercial caliber software that uses the methodology that has been developed in this thesis for a single month and expand the results to full year analysis, (3) extend the results of this thesis to integrate into whole building uncertainty analysis ( both demand and supply side). The latter research follow-up is currently undertaken in an EFRI-SEED project on risk conscious design and retrofit. This research will focus on three levels of integration (full dynamic integration, weak coupling, no coupling) between demand and supply where, as stated in Chapter 8, the results of this thesis will be used in the weak and no coupling modes. The results of that ongoing research may revolutionize the way we perform whole building uncertainty analyses in the future.

# APPENDIX A

# DETERMINISTIC VERSUS PROBABILISTIC COMPARISON

# (OFFICE)

Table A.1: Office System 1; first year (0.75 Mean)

| Deterministic KWH | Probabilistic KWH | % Difference | Bin Size | % Probability | % Cumulative |
|---|---|---|---|---|---|
| 2929 | | | | | |
| | 3040 | 3.79 | 11.00 | 2.20 | 100.00 |
| | 3060 | 4.47 | 80.00 | 16.00 | 97.80 |
| | 3080 | 5.16 | 41.00 | 8.20 | 81.80 |
| | 3100 | 5.84 | 46.00 | 9.20 | 73.60 |
| | 3120 | 6.52 | 66.00 | 13.20 | 64.40 |
| | 3140 | 7.20 | 5.00 | 1.00 | 51.20 |
| | 3160 | 7.89 | 21.00 | 4.20 | 50.20 |
| | 3180 | 8.57 | 31.00 | 6.20 | 46.00 |
| | 3200 | 9.25 | 66.00 | 13.20 | 39.80 |
| | 3220 | 9.94 | 37.00 | 7.40 | 26.60 |
| | 3240 | 10.62 | 85.00 | 17.00 | 19.20 |
| | 3260 | 11.30 | 10.00 | 2.00 | 2.20 |
| | 3280 | 11.98 | 1.00 | 0.20 | 0.20 |
| | | | 500 | | |

Table A.2: Office System 1; 1st year average

| Deterministic KWH | Probabilistic KWH | % Difference | Bin Size | % Probability | % Cumulative |
|---|---|---|---|---|---|
| 2929 | | | | | |
| | 2900 | -0.99 | 0.00 | 0.00 | 100.00 |
| | 2920 | -0.31 | 0.00 | 0.00 | 100.00 |
| | 2940 | 0.38 | 124.00 | 8.27 | 100.00 |
| | 2960 | 1.06 | 132.00 | 8.80 | 91.73 |
| | 2980 | 1.74 | 147.00 | 9.80 | 82.93 |
| | 3000 | 2.42 | 108.00 | 7.20 | 73.13 |
| | 3020 | 3.11 | 121.00 | 8.07 | 65.93 |
| | 3040 | 3.79 | 81.00 | 5.40 | 57.87 |
| | 3060 | 4.47 | 97.00 | 6.47 | 52.47 |
| | 3080 | 5.16 | 49.00 | 3.27 | 46.00 |
| | 3100 | 5.84 | 51.00 | 3.40 | 42.73 |
| | 3120 | 6.52 | 123.00 | 8.20 | 39.33 |
| | 3140 | 7.20 | 77.00 | 5.13 | 31.13 |
| | 3160 | 7.89 | 84.00 | 5.60 | 26.00 |
| | 3180 | 8.57 | 103.00 | 6.87 | 20.40 |
| | 3200 | 9.25 | 70.00 | 4.67 | 13.53 |
| | 3220 | 9.94 | 37.00 | 2.47 | 8.87 |
| | 3240 | 10.62 | 85.00 | 5.67 | 6.40 |
| | 3260 | 11.30 | 10.00 | 0.67 | 0.73 |
| | 3280 | 11.98 | 1.00 | 0.07 | 0.07 |
| | | | 1500 | | |

Table A.3: Office System 1; 5 years (0.75 Mean)

| Deterministic KWH | Probabilistic KWH | % Difference | Bin Size | % Probability | % Cumulative |
|---|---|---|---|---|---|
| 2929 | | | | | |
| | 3120 | 6.52 | 21.00 | 4.20 | 100.00 |
| | 3140 | 7.20 | 51.00 | 10.20 | 95.80 |
| | 3160 | 7.89 | 51.00 | 10.20 | 85.60 |
| | 3180 | 8.57 | 55.00 | 11.00 | 75.40 |
| | 3200 | 9.25 | 70.00 | 14.00 | 64.40 |
| | 3220 | 9.94 | 10.00 | 2.00 | 50.40 |
| | 3240 | 10.62 | 4.00 | 0.80 | 48.40 |
| | 3260 | 11.30 | 38.00 | 7.60 | 47.60 |
| | 3280 | 11.98 | 54.00 | 10.80 | 40.00 |
| | 3300 | 12.67 | 31.00 | 6.20 | 29.20 |
| | 3320 | 13.35 | 64.00 | 12.80 | 23.00 |
| | 3340 | 14.03 | 50.00 | 10.00 | 10.20 |
| | 3360 | 14.71 | 1.00 | 0.20 | 0.20 |
| | | | 500 | | |

Table A.4: Office System 1; 5 years average

| Deterministic KWH | Probabilistic KWH | % Difference | Bin Size | % Probability | % Cumulative |
|---|---|---|---|---|---|
| 2929 | | | | | |
| | 2940 | 0.38 | 13.00 | 0.87 | 100.00 |
| | 2960 | 1.06 | 55.00 | 3.67 | 99.13 |
| | 2980 | 1.74 | 58.00 | 3.87 | 95.47 |
| | 3000 | 2.42 | 136.00 | 9.07 | 91.60 |
| | 3020 | 3.11 | 128.00 | 8.53 | 82.53 |
| | 3040 | 3.79 | 65.00 | 4.33 | 74.00 |
| | 3060 | 4.47 | 141.00 | 9.40 | 69.67 |
| | 3080 | 5.16 | 37.00 | 2.47 | 60.27 |
| | 3100 | 5.84 | 70.00 | 4.67 | 57.80 |
| | 3120 | 6.52 | 44.00 | 2.93 | 53.13 |
| | 3140 | 7.20 | 65.00 | 4.33 | 50.20 |
| | 3160 | 7.89 | 64.00 | 4.27 | 45.87 |
| | 3180 | 8.57 | 114.00 | 7.60 | 41.60 |
| | 3200 | 9.25 | 115.00 | 7.67 | 34.00 |
| | 3220 | 9.94 | 53.00 | 3.53 | 26.33 |
| | 3240 | 10.62 | 80.00 | 5.33 | 22.80 |
| | 3260 | 11.30 | 62.00 | 4.13 | 17.47 |
| | 3280 | 11.98 | 54.00 | 3.60 | 13.33 |
| | 3300 | 12.67 | 31.00 | 2.07 | 9.73 |
| | 3320 | 13.35 | 64.00 | 4.27 | 7.67 |
| | 3340 | 14.03 | 50 | 3.33 | 3.40 |
| | 3360 | 14.71 | 1 | 0.07 | 0.07 |
| | | | 1500 | | |

Table A.5: Office System 2; First year (0.75 Mean)

| Deterministic KWH | Probabilistic KWH | % Difference | Bin Size | % Probability | % Cumulative |
|---|---|---|---|---|---|
| 3773 | | | | | |
| | 3950 | 4.69 | 1 | 0.20 | 100.00 |
| | 3960 | 4.96 | 1 | 0.20 | 99.80 |
| | 3970 | 5.22 | 2 | 0.40 | 99.60 |
| | 3980 | 5.49 | 21 | 4.20 | 99.20 |
| | 3990 | 5.75 | 24 | 4.80 | 95.00 |
| | 4000 | 6.02 | 61 | 12.20 | 90.20 |
| | 4010 | 6.28 | 55 | 11.00 | 78.00 |
| | 4020 | 6.55 | 107 | 21.40 | 67.00 |
| | 4030 | 6.81 | 59 | 11.80 | 45.60 |
| | 4040 | 7.08 | 86 | 17.20 | 33.80 |
| | 4050 | 7.34 | 36 | 7.20 | 16.60 |
| | 4060 | 7.61 | 29 | 5.80 | 9.40 |
| | 4070 | 7.87 | 10 | 2.00 | 3.60 |
| | 4080 | 8.14 | 8 | 1.60 | 1.60 |
| | | | 500 | | |

Table A.6: Office System 2; First year average

| Deterministic KWH | Probabilistic KWH | % Difference | Bin Size | % Probability | % Cumulative |
|---|---|---|---|---|---|
| 3773 | | | | | |
| | 3790 | 0.45 | 5 | 0.33 | 100.00 |
| | 3800 | 0.72 | 17 | 1.13 | 99.67 |
| | 3810 | 0.98 | 47 | 3.13 | 98.53 |
| | 3820 | 1.25 | 85 | 5.67 | 95.40 |
| | 3830 | 1.51 | 130 | 8.67 | 89.73 |
| | 3840 | 1.78 | 95 | 6.33 | 81.07 |
| | 3850 | 2.04 | 78 | 5.20 | 74.73 |
| | 3860 | 2.31 | 37 | 2.47 | 69.53 |
| | 3870 | 2.57 | 9 | 0.60 | 67.07 |
| | 3880 | 2.84 | 17 | 1.13 | 66.47 |
| | 3890 | 3.10 | 34 | 2.27 | 65.33 |
| | 3900 | 3.37 | 67 | 4.47 | 63.07 |
| | 3910 | 3.63 | 76 | 5.07 | 58.60 |
| | 3920 | 3.90 | 107 | 7.13 | 53.53 |
| | 3930 | 4.16 | 80 | 5.33 | 46.40 |
| | 3940 | 4.43 | 72 | 4.80 | 41.07 |
| | 3950 | 4.69 | 28 | 1.87 | 36.27 |
| | 3960 | 4.96 | 16 | 1.07 | 34.40 |
| | 3970 | 5.22 | 4 | 0.27 | 33.33 |
| | 3980 | 5.49 | 21 | 1.40 | 33.07 |
| | 3990 | 5.75 | 24 | 1.60 | 31.67 |
| | 4000 | 6.02 | 61 | 4.07 | 30.07 |
| | 4010 | 6.28 | 55 | 3.67 | 26.00 |
| | 4020 | 6.55 | 107 | 7.13 | 22.33 |
| | 4030 | 6.81 | 59 | 3.93 | 15.20 |
| | 4040 | 7.08 | 86 | 5.73 | 11.27 |
| | 4050 | 7.34 | 36 | 2.40 | 5.53 |
| | 4060 | 7.61 | 29 | 1.93 | 3.13 |
| | 4070 | 7.87 | 10 | 0.67 | 1.20 |
| | 4080 | 8.14 | 8 | 0.53 | 0.53 |
| | | | 1500 | | |

Table A.7: Office System 2; 5 years (Mean 0.75)

| Deterministic KWH | Probabilistic KWH | % Difference | Bin Size | % Probability | % Cumulative |
|---|---|---|---|---|---|
| 3773 | | | | | |
| | 4080 | 8.14 | 5 | 1.00 | 100.00 |
| | 4090 | 8.40 | 4 | 0.80 | 99.00 |
| | 4100 | 8.67 | 6 | 1.20 | 98.20 |
| | 4110 | 8.93 | 37 | 7.40 | 97.00 |
| | 4120 | 9.20 | 45 | 9.00 | 89.60 |
| | 4130 | 9.46 | 87 | 17.40 | 80.60 |
| | 4140 | 9.73 | 61 | 12.20 | 63.20 |
| | 4150 | 9.99 | 108 | 21.60 | 51.00 |
| | 4160 | 10.26 | 47 | 9.40 | 29.40 |
| | 4170 | 10.52 | 59 | 11.80 | 20.00 |
| | 4180 | 10.79 | 16 | 3.20 | 8.20 |
| | 4190 | 11.05 | 22 | 4.40 | 5.00 |
| | 4200 | 11.32 | 3 | 0.60 | 0.60 |
| | | | 500 | | |

Table A.8: Office System 2; 5 years average

| Deterministic KWH | Probabilistic KWH | % Difference | Bin Size | % Probability | % Cumulative |
|---|---|---|---|---|---|
| 3773 | | | | | |
| | 3830 | 1.51 | 5 | 0.33 | 100.00 |
| | 3840 | 1.78 | 36 | 2.40 | 99.67 |
| | 3850 | 2.04 | 76 | 5.07 | 97.27 |
| | 3860 | 2.31 | 73 | 4.87 | 92.20 |
| | 3870 | 2.57 | 123 | 8.20 | 87.33 |
| | 3880 | 2.84 | 101 | 6.73 | 79.13 |
| | 3890 | 3.10 | 45 | 3.00 | 72.40 |
| | 3900 | 3.37 | 26 | 1.73 | 69.40 |
| | 3910 | 3.63 | 15 | 1.00 | 67.67 |
| | 3920 | 3.90 | 0 | 0.00 | 66.67 |
| | 3930 | 4.16 | 0 | 0.00 | 66.67 |
| | 3940 | 4.43 | 2 | 0.13 | 66.67 |
| | 3950 | 4.69 | 6 | 0.40 | 66.53 |
| | 3960 | 4.96 | 21 | 1.40 | 66.13 |
| | 3970 | 5.22 | 40 | 2.67 | 64.73 |
| | 3980 | 5.49 | 69 | 4.60 | 62.07 |
| | 3990 | 5.75 | 92 | 6.13 | 57.47 |
| | 4000 | 6.02 | 89 | 5.93 | 51.33 |
| | 4010 | 6.28 | 76 | 5.07 | 45.40 |
| | 4020 | 6.55 | 65 | 4.33 | 40.33 |
| | 4030 | 6.81 | 25 | 1.67 | 36.00 |
| | 4040 | 7.08 | 14 | 0.93 | 34.33 |
| | 4050 | 7.34 | 1 | 0.07 | 33.40 |
| | 4060 | 7.61 | 0 | 0.00 | 33.33 |
| | 4070 | 7.87 | 0 | 0.00 | 33.33 |
| | 4080 | 8.14 | 5 | 0.33 | 33.33 |
| | 4090 | 8.40 | 4 | 0.27 | 33.00 |
| | 4100 | 8.67 | 6 | 0.40 | 32.73 |
| | 4110 | 8.93 | 37 | 2.47 | 32.33 |
| | 4120 | 9.20 | 45 | 3.00 | 29.87 |
| | 4130 | 9.46 | 87 | 5.80 | 26.87 |
| | 4140 | 9.73 | 61 | 4.07 | 21.07 |
| | 4150 | 9.99 | 108 | 7.20 | 17.00 |
| | 4160 | 10.26 | 47 | 3.13 | 9.80 |
| | 4170 | 10.52 | 59 | 3.93 | 6.67 |
| | 4180 | 10.79 | 16 | 1.07 | 2.73 |
| | 4190 | 11.05 | 22 | 1.47 | 1.67 |
| | 4200 | 11.32 | 3 | 0.20 | 0.20 |
| | | | 1500 | | |

Table A.9: Office; System 3; first year (Mean 0.75)

| Deterministic KWH | Probabilistic KWH | % Difference | Bin Size | % Probability | % Cumulative |
|---|---|---|---|---|---|
| 4002 | | | | | |
| | 3050 | -23.79 | 4 | 0.80 | 0.80 |
| | 3100 | -22.54 | 3 | 0.60 | 1.40 |
| | 4150 | 3.70 | 4 | 0.80 | 98.60 |
| | 4250 | 6.20 | 390 | 78.00 | 97.80 |
| | 4300 | 7.45 | 99 | 19.80 | 19.80 |
| | | | 500 | | |

Table A.10: Office System 3; 1st year average

| Deterministic KWH | Probabilistic KWH | % Difference | Bin Size | % Probability | % Cumulative |
|---|---|---|---|---|---|
| 4002 | | | | | |
| | 3050 | -23.79 | 4.00 | 0.27 | 0.27 |
| | 3100 | -22.54 | 3.00 | 0.20 | 0.47 |
| | 3900 | -2.55 | 0.00 | 0.00 | 0.47 |
| | 4000 | -0.05 | 7.00 | 0.47 | 0.93 |
| | 4010 | 0.20 | 20.00 | 1.33 | 99.07 |
| | 4020 | 0.45 | 47.00 | 3.13 | 97.73 |
| | 4030 | 0.70 | 80.00 | 5.33 | 94.60 |
| | 4040 | 0.95 | 129.00 | 8.60 | 89.27 |
| | 4050 | 1.20 | 118.00 | 7.87 | 80.67 |
| | 4060 | 1.45 | 79.00 | 5.27 | 72.80 |
| | 4070 | 1.70 | 20.00 | 1.33 | 67.53 |
| | 4080 | 1.95 | 0.00 | 0.00 | 66.20 |
| | 4090 | 2.20 | 4.00 | 0.27 | 66.20 |
| | 4100 | 2.45 | 2.00 | 0.13 | 65.93 |
| | 4110 | 2.70 | 43.00 | 2.87 | 65.80 |
| | 4120 | 2.95 | 78.00 | 5.20 | 62.93 |
| | 4130 | 3.20 | 118.00 | 7.87 | 57.73 |
| | 4140 | 3.45 | 44.00 | 2.93 | 49.87 |
| | 4150 | 3.70 | 77.00 | 5.13 | 46.93 |
| | 4160 | 3.95 | 69.00 | 4.60 | 41.80 |
| | 4170 | 4.20 | 30.00 | 2.00 | 37.20 |
| | 4180 | 4.45 | 22.00 | 1.47 | 35.20 |
| | 4190 | 4.70 | 7.00 | 0.47 | 33.73 |
| | 4200 | 4.95 | 6.00 | 0.40 | 33.27 |
| | 4210 | 5.20 | 4.00 | 0.27 | 32.87 |
| | 4250 | 6.20 | 390.00 | 26.00 | 32.60 |
| | 4300 | 7.45 | 99.00 | 6.60 | 6.60 |
| | | | 1500 | | |

Table A.11: Office System 3; 5 years (Mean 0.75)

| Deterministic KWH | Probabilistic KWH | % Difference | Bin Size | % Probability | % Cumulative |
|---|---|---|---|---|---|
| 4002 | | | | | |
| | 3050 | -23.79 | 4.00 | 0.80 | 0.80 |
| | 3100 | -22.54 | 3.00 | 0.60 | 1.40 |
| | 4300 | 7.45 | 13.00 | 2.60 | 98.60 |
| | 4350 | 8.70 | 400.00 | 80.00 | 96.00 |
| | 4400 | 9.95 | 80.00 | 16.00 | 16.00 |
| | | | 500 | | |

Table A.12: Office System 3; 5 years average

| Deterministic KWH | Probabilistic KWH | % Difference | Bin Size | % Probability | % Cumulative |
|---|---|---|---|---|---|
| 4002 | | | | | |
| | 3050 | -23.79 | 4.00 | 0.27 | 0.27 |
| | 3100 | -22.54 | 3.00 | 0.20 | 0.47 |
| | 4030 | 0.70 | 0.00 | 0.00 | 99.53 |
| | 4040 | 0.95 | 4.00 | 0.27 | 99.53 |
| | 4050 | 1.20 | 20.00 | 1.33 | 99.27 |
| | 4060 | 1.45 | 60.00 | 4.00 | 97.93 |
| | 4070 | 1.70 | 88.00 | 5.87 | 93.93 |
| | 4080 | 1.95 | 123.00 | 8.20 | 88.07 |
| | 4090 | 2.20 | 113.00 | 7.53 | 79.87 |
| | 4100 | 2.45 | 56.00 | 3.73 | 72.33 |
| | 4110 | 2.70 | 36.00 | 2.40 | 68.60 |
| | 4120 | 2.95 | 0.00 | 0.00 | 66.20 |
| | 4130 | 3.20 | 0.00 | 0.00 | 66.20 |
| | 4140 | 3.45 | 0.00 | 0.00 | 66.20 |
| | 4150 | 3.70 | 0.00 | 0.00 | 66.20 |
| | 4160 | 3.95 | 0.00 | 0.00 | 66.20 |
| | 4170 | 4.20 | 3.00 | 0.20 | 66.20 |
| | 4180 | 4.45 | 7.00 | 0.47 | 66.00 |
| | 4190 | 4.70 | 33.00 | 2.20 | 65.53 |
| | 4200 | 4.95 | 82.00 | 5.47 | 63.33 |
| | 4210 | 5.20 | 45.00 | 3.00 | 57.87 |
| | 4220 | 5.45 | 105.00 | 7.00 | 54.87 |
| | 4230 | 5.70 | 85.00 | 5.67 | 47.87 |
| | 4240 | 5.95 | 53.00 | 3.53 | 42.20 |
| | 4250 | 6.20 | 15.00 | 1.00 | 38.67 |
| | 4260 | 6.45 | 38.00 | 2.53 | 37.67 |
| | 4270 | 6.70 | 20.00 | 1.33 | 35.13 |
| | 4280 | 6.95 | 8.00 | 0.53 | 33.80 |
| | 4290 | 7.20 | 5.00 | 0.33 | 33.27 |
| | 4300 | 7.45 | 14.00 | 0.93 | 32.93 |
| | 4350 | 8.70 | 400.00 | 26.67 | 32.00 |
| | 4400 | 9.95 | 80.00 | 5.33 | 5.33 |
| | | | 1500 | | |

Table A.13: Office; System 4; first year (0.75 Mean)

| Deterministic KWH | Probabilistic KWH | % Difference | Bin Size | % Probability | % Cumulative |
|---|---|---|---|---|---|
| 3733 | | | | | |
| | 3880 | 3.94 | 1.00 | 0.20 | 100.00 |
| | 3900 | 4.47 | 11.00 | 2.20 | 99.80 |
| | 3920 | 5.01 | 61.00 | 12.20 | 97.60 |
| | 3940 | 5.55 | 35.00 | 7.00 | 85.40 |
| | 3960 | 6.08 | 64.00 | 12.80 | 78.40 |
| | 3980 | 6.62 | 57.00 | 11.40 | 65.60 |
| | 4000 | 7.15 | 22.00 | 4.40 | 54.20 |
| | 4020 | 7.69 | 79.00 | 15.80 | 49.80 |
| | 4040 | 8.22 | 50.00 | 10.00 | 34.00 |
| | 4060 | 8.76 | 42.00 | 8.40 | 24.00 |
| | 4080 | 9.30 | 71.00 | 14.20 | 15.60 |
| | 4100 | 9.83 | 7.00 | 1.40 | 1.40 |
| | | | | | |
| | | | | | |
| | | | 500 | | |

Table A.14: Office System 4; 1st year average

| Deterministic KWH | Probabilistic KWH | % Difference | Bin Size | % Probability | % Cumulative |
|---|---|---|---|---|---|
| 3733 | | | | | |
| | 3720 | -0.35 | 9 | 0.60 | 0.60 |
| | 3730 | -0.08 | 42 | 2.80 | 3.40 |
| | 3740 | 0.19 | 86 | 5.73 | 96.60 |
| | 3750 | 0.46 | 32 | 2.13 | 90.87 |
| | 3760 | 0.72 | 2 | 0.13 | 88.73 |
| | 3770 | 0.99 | 45 | 3.00 | 88.60 |
| | 3780 | 1.26 | 105 | 7.00 | 85.60 |
| | 3790 | 1.53 | 75 | 5.00 | 78.60 |
| | 3800 | 1.79 | 95 | 6.33 | 73.60 |
| | 3810 | 2.06 | 8 | 0.53 | 67.27 |
| | 3820 | 2.33 | 1 | 0.07 | 66.73 |
| | 3830 | 2.60 | 0 | 0.00 | 66.67 |
| | 3840 | 2.87 | 1 | 0.07 | 66.67 |
| | 3850 | 3.13 | 0 | 0.00 | 66.60 |
| | 3860 | 3.40 | 0 | 0.00 | 66.60 |
| | 3870 | 3.67 | 0 | 0.00 | 66.60 |
| | 3880 | 3.94 | 1 | 0.07 | 66.60 |
| | 3890 | 4.21 | 0 | 0.00 | 66.53 |
| | 3900 | 4.47 | 12 | 0.80 | 66.53 |
| | 3910 | 4.74 | 0 | 0.00 | 65.73 |
| | 3920 | 5.01 | 77 | 5.13 | 65.73 |
| | 3930 | 5.28 | 0 | 0.00 | 60.60 |
| | 3940 | 5.55 | 132 | 8.80 | 60.60 |
| | 3950 | 5.81 | 0 | 0.00 | 51.80 |
| | 3960 | 6.08 | 121 | 8.07 | 51.80 |
| | 3970 | 6.35 | 0 | 0.00 | 43.73 |
| | 3980 | 6.62 | 163 | 10.87 | 43.73 |
| | 3990 | 6.88 | 0 | 0.00 | 32.87 |
| | 4000 | 7.15 | 119 | 7.93 | 32.87 |
| | 4010 | 7.42 | 0 | 0.00 | 24.93 |
| | 4020 | 7.69 | 195 | 13.00 | 24.93 |
| | 4030 | 7.96 | 0 | 0.00 | 11.93 |
| | 4040 | 8.22 | 59 | 3.93 | 11.93 |
| | 4050 | 8.49 | 0 | 0.00 | 8.00 |
| | 4060 | 8.76 | 42 | 2.80 | 8.00 |
| | 4070 | 9.03 | 0 | 0.00 | 5.20 |
| | 4080 | 9.30 | 71 | 4.73 | 5.20 |
| | 4090 | 9.56 | 0 | 0.00 | 0.47 |
| | 4100 | 9.83 | 7 | 0.47 | 0.47 |
| | | | 1500.00 | | |

Table A.15: Office System 4; 5 years (Mean 0.75)

| Deterministic KWH | Probabilistic KWH | % Difference | Bin Size | % Probability | % Cumulative |
|---|---|---|---|---|---|
| 3733 | | | | | |
| | 3920 | 5.01 | 3.00 | 0.60 | 100.00 |
| | 3940 | 5.55 | 51.00 | 10.20 | 99.40 |
| | 3960 | 6.08 | 31.00 | 6.20 | 89.20 |
| | 3980 | 6.62 | 37.00 | 7.40 | 83.00 |
| | 4000 | 7.15 | 32.00 | 6.40 | 75.60 |
| | 4020 | 7.69 | 22.00 | 4.40 | 69.20 |
| | 4040 | 8.22 | 1.00 | 0.20 | 64.80 |
| | 4060 | 8.76 | 0.00 | 0.00 | 64.60 |
| | 4080 | 9.30 | 6.00 | 1.20 | 64.60 |
| | 4100 | 9.83 | 85.00 | 17.00 | 63.40 |
| | 4120 | 10.37 | 47.00 | 9.40 | 46.40 |
| | 4140 | 10.90 | 72.00 | 14.40 | 37.00 |
| | 4160 | 11.44 | 60.00 | 12.00 | 22.60 |
| | 4180 | 11.97 | 51.00 | 10.20 | 10.60 |
| | 4200 | 12.51 | 2.00 | 0.40 | 0.40 |
| | | | 500.00 | | |

Table A.16: Office System 4; 5 years average

| Deterministic KWH | Probabilistic KWH | % Difference | Bin Size | % Probability | % Cumulative |
|---|---|---|---|---|---|
| 3733 | | | | | |
| | 3750 | 0.46 | 2 | 0.13 | 100.00 |
| | 3760 | 0.72 | 46 | 3.07 | 99.87 |
| | 3770 | 0.99 | 61 | 4.07 | 96.80 |
| | 3780 | 1.26 | 41 | 2.73 | 92.73 |
| | 3790 | 1.53 | 24 | 1.60 | 90.00 |
| | 3800 | 1.79 | 11 | 0.73 | 88.40 |
| | 3810 | 2.06 | 68 | 4.53 | 87.67 |
| | 3820 | 2.33 | 127 | 8.47 | 83.13 |
| | 3830 | 2.60 | 104 | 6.93 | 74.67 |
| | 3840 | 2.87 | 69 | 4.60 | 67.73 |
| | 3850 | 3.13 | 69 | 4.60 | 63.13 |
| | 3860 | 3.40 | 54 | 3.60 | 58.53 |
| | 3870 | 3.67 | 23 | 1.53 | 54.93 |
| | 3880 | 3.94 | 30 | 2.00 | 53.40 |
| | 3890 | 4.21 | 49 | 3.27 | 51.40 |
| | 3900 | 4.47 | 53 | 3.53 | 48.13 |
| | 3910 | 4.74 | 83 | 5.53 | 44.60 |
| | 3920 | 5.01 | 69 | 4.60 | 39.07 |
| | 3930 | 5.28 | 19 | 1.27 | 34.47 |
| | 3940 | 5.55 | 52 | 3.47 | 33.20 |
| | 3950 | 5.81 | 0 | 0.00 | 29.73 |
| | 3960 | 6.08 | 31 | 2.07 | 29.73 |
| | 3970 | 6.35 | 0 | 0.00 | 27.67 |
| | 3980 | 6.62 | 37 | 2.47 | 27.67 |
| | 3990 | 6.88 | 0 | 0.00 | 25.20 |
| | 4000 | 7.15 | 32 | 2.13 | 25.20 |
| | 4010 | 7.42 | 0 | 0.00 | 23.07 |
| | 4020 | 7.69 | 22 | 1.47 | 23.07 |
| | 4030 | 7.96 | 0 | 0.00 | 21.60 |
| | 4040 | 8.22 | 1 | 0.07 | 21.60 |
| | 4050 | 8.49 | 0 | 0.00 | 21.53 |
| | 4060 | 8.76 | 0 | 0.00 | 21.53 |
| | 4070 | 9.03 | 0 | 0.00 | 21.53 |
| | 4080 | 9.30 | 6 | 0.40 | 21.53 |
| | 4090 | 9.56 | 0 | 0.00 | 21.13 |
| | 4100 | 9.83 | 85 | 5.67 | 21.13 |
| | 4110 | 10.10 | 0 | 0.00 | 15.47 |
| | 4120 | 10.37 | 47 | 3.13 | 15.47 |

Table A.16. continued

| | | | | | |
|---|---|---|---|---|---|
| | 4130 | 10.63 | 0 | 0.00 | 12.33 |
| | 4140 | 10.90 | 72 | 4.80 | 12.33 |
| | 4150 | 11.17 | 0 | 0.00 | 7.53 |
| | 4160 | 11.44 | 60 | 4.00 | 7.53 |
| | 4170 | 11.71 | 0 | 0.00 | 3.53 |
| | 4180 | 11.97 | 51 | 3.40 | 3.53 |
| | 4190 | 12.24 | 0 | 0.00 | 0.13 |
| | 4200 | 12.51 | 2 | 0.13 | 0.13 |
| | | | 1500.00 | | |

Table A.17: Office; System 5; first year (Mean 0.75)

| Deterministic KWH | Probabilistic KWH | % Difference | Bin Size | % Probability | % Cumulative |
|---|---|---|---|---|---|
| 2338 | | | | | |
| | 2360 | 0.94 | 14.00 | 2.80 | 100.00 |
| | 2380 | 1.80 | 116.00 | 23.20 | 97.20 |
| | 2400 | 2.65 | 14.00 | 2.80 | 74.00 |
| | 2420 | 3.51 | 85.00 | 17.00 | 71.20 |
| | 2440 | 4.36 | 44.00 | 8.80 | 54.20 |
| | 2460 | 5.22 | 0.00 | 0.00 | 45.40 |
| | 2480 | 6.07 | 11.00 | 2.20 | 45.40 |
| | 2500 | 6.93 | 39.00 | 7.80 | 43.20 |
| | 2520 | 7.78 | 60.00 | 12.00 | 35.40 |
| | 2540 | 8.64 | 19.00 | 3.80 | 23.40 |
| | 2560 | 9.50 | 92.00 | 18.40 | 19.60 |
| | 2580 | 10.35 | 6.00 | 1.20 | 1.20 |
| | | | 500 | | |

Table A.18: Office System 5; 1st year average

| Deterministic KWH | Probabilistic KWH | % Difference | Bin Size | % Probability | % Cumulative |
|---|---|---|---|---|---|
| 2338 | | | | | |
| | 2280 | -2.48 | 2.00 | 0.13 | 0.13 |
| | 2300 | -1.63 | 115.00 | 7.67 | 7.80 |
| | 2320 | -0.77 | 1.00 | 0.07 | 7.87 |
| | 2340 | 0.09 | 314.00 | 20.93 | 92.13 |
| | 2360 | 0.94 | 92.00 | 6.13 | 71.20 |
| | 2380 | 1.80 | 243.00 | 16.20 | 65.07 |
| | 2400 | 2.65 | 133.00 | 8.87 | 48.87 |
| | 2420 | 3.51 | 89.00 | 5.93 | 40.00 |
| | 2440 | 4.36 | 45.00 | 3.00 | 34.07 |
| | 2460 | 5.22 | 38.00 | 2.53 | 31.07 |
| | 2480 | 6.07 | 89.00 | 5.93 | 28.53 |
| | 2500 | 6.93 | 43.00 | 2.87 | 22.60 |
| | 2520 | 7.78 | 165.00 | 11.00 | 19.73 |
| | 2540 | 8.64 | 33.00 | 2.20 | 8.73 |
| | 2560 | 9.50 | 92.00 | 6.13 | 6.53 |
| | 2580 | 10.35 | 6.00 | 0.40 | 0.40 |
| | | | 1500 | | |

Table A.19: Office System 5; 5 years (Mean 0.75)

| Deterministic KWH | Probabilistic KWH | % Difference | Bin Size | % Probability | % Cumulative |
|---|---|---|---|---|---|
| 2338 | | | | | |
| | 2420 | 3.51 | 2.00 | 0.40 | 100.00 |
| | 2440 | 4.36 | 33.00 | 6.60 | 99.60 |
| | 2460 | 5.22 | 101.00 | 20.20 | 93.00 |
| | 2480 | 6.07 | 19.00 | 3.80 | 72.80 |
| | 2500 | 6.93 | 106.00 | 21.20 | 69.00 |
| | 2520 | 7.78 | 13.00 | 2.60 | 47.80 |
| | 2540 | 8.64 | 1.00 | 0.20 | 45.20 |
| | 2560 | 9.50 | 9.00 | 1.80 | 45.00 |
| | 2580 | 10.35 | 79.00 | 15.80 | 43.20 |
| | 2600 | 11.21 | 27.00 | 5.40 | 27.40 |
| | 2620 | 12.06 | 19.00 | 3.80 | 22.00 |
| | 2640 | 12.92 | 89.00 | 17.80 | 18.20 |
| | 2660 | 13.77 | 2.00 | 0.40 | 0.40 |
| | | | 500 | | |

Table A.20: Office System 5; 5 years average

| Deterministic KWH | Probabilistic KWH | % Difference | Bin Size | % Probability | % Cumulative |
|---|---|---|---|---|---|
| 2338 | | | | | |
| | 2320 | -0.77 | 115.00 | 7.67 | 7.67 |
| | 2340 | 0.09 | 2.00 | 0.13 | 92.33 |
| | 2360 | 0.94 | 207.00 | 13.80 | 92.20 |
| | 2380 | 1.80 | 110.00 | 7.33 | 78.40 |
| | 2400 | 2.65 | 115.00 | 7.67 | 71.07 |
| | 2420 | 3.51 | 97.00 | 6.47 | 63.40 |
| | 2440 | 4.36 | 142.00 | 9.47 | 56.93 |
| | 2460 | 5.22 | 109.00 | 7.27 | 47.47 |
| | 2480 | 6.07 | 21.00 | 1.40 | 40.20 |
| | 2500 | 6.93 | 109.00 | 7.27 | 38.80 |
| | 2520 | 7.78 | 101.00 | 6.73 | 31.53 |
| | 2540 | 8.64 | 20.00 | 1.33 | 24.80 |
| | 2560 | 9.50 | 53.00 | 3.53 | 23.47 |
| | 2580 | 10.35 | 162.00 | 10.80 | 19.93 |
| | 2600 | 11.21 | 27.00 | 1.80 | 9.13 |
| | 2620 | 12.06 | 19.00 | 1.27 | 7.33 |
| | 2640 | 12.92 | 89.00 | 5.93 | 6.07 |
| | 2660 | 13.77 | 2.00 | 0.13 | 0.13 |
| | | | 1500 | | |

Table A.21: Office System 6; first year (Mean 0.75)

| Deterministic KWH | Probabilistic KWH | % Difference | Bin Size | % Probability | % Cumulative |
|---|---|---|---|---|---|
| 3219 | | | | | |
| | 3280 | 1.89 | 1.00 | 0.20 | 100.00 |
| | 3290 | 2.21 | 1.00 | 0.20 | 99.80 |
| | 3300 | 2.52 | 18.00 | 3.60 | 99.60 |
| | 3310 | 2.83 | 29.00 | 5.80 | 96.00 |
| | 3320 | 3.14 | 59.00 | 11.80 | 90.20 |
| | 3330 | 3.45 | 75.00 | 15.00 | 78.40 |
| | 3340 | 3.76 | 105.00 | 21.00 | 63.40 |
| | 3350 | 4.07 | 87.00 | 17.40 | 42.40 |
| | 3360 | 4.38 | 54.00 | 10.80 | 25.00 |
| | 3370 | 4.69 | 32.00 | 6.40 | 14.20 |
| | 3380 | 5.00 | 21.00 | 4.20 | 7.80 |
| | 3390 | 5.31 | 15.00 | 3.00 | 3.60 |
| | 3400 | 5.62 | 3.00 | 0.60 | 0.60 |
| | | | 500 | | |

Table A.22: Office System 6; First year average

| Deterministic KWH | Probabilistic KWH | % Difference | Bin Size | % Probability | % Cumulative |
|---|---|---|---|---|---|
| 3219 | | | | | |
| | 3160 | -1.83 | 1.00 | 0.07 | 0.07 |
| | 3170 | -1.52 | 1.00 | 0.07 | 0.13 |
| | 3180 | -1.21 | 118.00 | 7.87 | 8.00 |
| | 3190 | -0.90 | 35.00 | 2.33 | 10.33 |
| | 3200 | -0.59 | 28.00 | 1.87 | 12.20 |
| | 3210 | -0.28 | 260.00 | 17.33 | 29.53 |
| | 3220 | 0.03 | 46.00 | 3.07 | 70.47 |
| | 3230 | 0.34 | 27.00 | 1.80 | 67.40 |
| | 3240 | 0.65 | 15.00 | 1.00 | 65.60 |
| | 3250 | 0.96 | 141.00 | 9.40 | 64.60 |
| | 3260 | 1.27 | 95.00 | 6.33 | 55.20 |
| | 3270 | 1.58 | 61.00 | 4.07 | 48.87 |
| | 3280 | 1.89 | 108.00 | 7.20 | 44.80 |
| | 3290 | 2.21 | 38.00 | 2.53 | 37.60 |
| | 3300 | 2.52 | 41.00 | 2.73 | 35.07 |
| | 3310 | 2.83 | 34.00 | 2.27 | 32.33 |
| | 3320 | 3.14 | 59.00 | 3.93 | 30.07 |
| | 3330 | 3.45 | 75.00 | 5.00 | 26.13 |
| | 3340 | 3.76 | 105.00 | 7.00 | 21.13 |
| | 3350 | 4.07 | 87.00 | 5.80 | 14.13 |
| | 3360 | 4.38 | 54.00 | 3.60 | 8.33 |
| | 3370 | 4.69 | 32.00 | 2.13 | 4.73 |
| | 3380 | 5.00 | 21.00 | 1.40 | 2.60 |
| | 3390 | 5.31 | 15.00 | 1.00 | 1.20 |
| | 3400 | 5.62 | 3.00 | 0.20 | 0.20 |
| | | | 1500 | | |

Table A.23: Office System 6; 5 years (0.75 Mean)

| Deterministic KWH | Probabilistic KWH | % Difference | Bin Size | % Probability | % Cumulative |
|---|---|---|---|---|---|
| 3219 | | | | | |
| | 3380 | 5.00 | 2.00 | 0.40 | 100.00 |
| | 3390 | 5.31 | 5.00 | 1.00 | 99.60 |
| | 3400 | 5.62 | 26.00 | 5.20 | 98.60 |
| | 3410 | 5.93 | 20.00 | 4.00 | 93.40 |
| | 3420 | 6.24 | 74.00 | 14.80 | 89.40 |
| | 3430 | 6.55 | 34.00 | 6.80 | 74.60 |
| | 3440 | 6.87 | 108.00 | 21.60 | 67.80 |
| | 3450 | 7.18 | 94.00 | 18.80 | 46.20 |
| | 3460 | 7.49 | 36.00 | 7.20 | 27.40 |
| | 3470 | 7.80 | 60.00 | 12.00 | 20.20 |
| | 3480 | 8.11 | 29.00 | 5.80 | 8.20 |
| | 3490 | 8.42 | 8.00 | 1.60 | 2.40 |
| | 3500 | 8.73 | 2.00 | 0.40 | 0.80 |
| | 3520 | 9.35 | 2.00 | 0.40 | 0.40 |
| | | | 500 | | |

Table A.24: Office System 6; 5 years average

| Deterministic KWH | Probabilistic KWH | % Difference | Bin Size | % Probability | % Cumulative |
|---|---|---|---|---|---|
| 3219 | | | | | |
| | 3180 | -1.21 | 1.00 | 0.07 | 0.07 |
| | 3190 | -0.90 | 0.00 | 0.00 | 0.07 |
| | 3200 | -0.59 | 3.00 | 0.20 | 0.27 |
| | 3210 | -0.28 | 116.00 | 7.73 | 8.00 |
| | 3220 | 0.03 | 48.00 | 3.20 | 92.00 |
| | 3230 | 0.34 | 169.00 | 11.27 | 88.80 |
| | 3240 | 0.65 | 111.00 | 7.40 | 77.53 |
| | 3250 | 0.96 | 41.00 | 2.73 | 70.13 |
| | 3260 | 1.27 | 11.00 | 0.73 | 67.40 |
| | 3270 | 1.58 | 0.00 | 0.00 | 66.67 |
| | 3280 | 1.89 | 0.00 | 0.00 | 66.67 |
| | 3290 | 2.21 | 9.00 | 0.60 | 66.67 |
| | 3300 | 2.52 | 22.00 | 1.47 | 66.07 |
| | 3310 | 2.83 | 44.00 | 2.93 | 64.60 |
| | 3320 | 3.14 | 140.00 | 9.33 | 61.67 |
| | 3330 | 3.45 | 76.00 | 5.07 | 52.33 |
| | 3340 | 3.76 | 125.00 | 8.33 | 47.27 |
| | 3350 | 4.07 | 40.00 | 2.67 | 38.93 |
| | 3360 | 4.38 | 33.00 | 2.20 | 36.27 |
| | 3370 | 4.69 | 10.00 | 0.67 | 34.07 |
| | 3380 | 5.00 | 3.00 | 0.20 | 33.40 |
| | 3390 | 5.31 | 5.00 | 0.33 | 33.20 |
| | 3400 | 5.62 | 26.00 | 1.73 | 32.87 |
| | 3410 | 5.93 | 20.00 | 1.33 | 31.13 |
| | 3420 | 6.24 | 74.00 | 4.93 | 29.80 |
| | 3430 | 6.55 | 34.00 | 2.27 | 24.87 |
| | 3440 | 6.87 | 108.00 | 7.20 | 22.60 |
| | 3450 | 7.18 | 94.00 | 6.27 | 15.40 |
| | 3460 | 7.49 | 36.00 | 2.40 | 9.13 |
| | 3470 | 7.80 | 60.00 | 4.00 | 6.73 |
| | 3480 | 8.11 | 29.00 | 1.93 | 2.73 |
| | 3490 | 8.42 | 12.00 | 0.80 | 0.80 |
| | | | 1500 | | |

Table A.25: Healthcare System 1; 1st year (0.75 Mean)

| Deterministic KWH | Probabilistic KWH | % Difference | Bin Size | % Probability | % Cumulative |
|---|---|---|---|---|---|
| 3016 | | | | | |
| | 3100 | 2.79 | 2.00 | 0.40 | 100.00 |
| | 3120 | 3.45 | 8.00 | 1.60 | 99.60 |
| | 3140 | 4.11 | 70.00 | 14.00 | 98.00 |
| | 3160 | 4.77 | 51.00 | 10.20 | 84.00 |
| | 3180 | 5.44 | 26.00 | 5.20 | 73.80 |
| | 3200 | 6.10 | 69.00 | 13.80 | 68.60 |
| | 3220 | 6.76 | 16.00 | 3.20 | 54.80 |
| | 3240 | 7.43 | 1.00 | 0.20 | 51.60 |
| | 3260 | 8.09 | 46.00 | 9.20 | 51.40 |
| | 3280 | 8.75 | 39.00 | 7.80 | 42.20 |
| | 3300 | 9.42 | 60.00 | 12.00 | 34.40 |
| | 3320 | 10.08 | 32.00 | 6.40 | 22.40 |
| | 3340 | 10.74 | 57.00 | 11.40 | 16.00 |
| | 3360 | 11.41 | 23.00 | 4.60 | 4.60 |
| | | | 500 | | |

Table A.26: Healthcare System 1; 1st year average

| Deterministic KWH | Probabilistic KWH | % Difference | Bin Size | % Probability | % Cumulative |
|---|---|---|---|---|---|
| 3016 | | | | | |
| | 2980 | -1.19 | 1.00 | 0.07 | 0.07 |
| | 2990 | -0.86 | 12.00 | 0.80 | 0.87 |
| | 3000 | -0.53 | 38.00 | 2.53 | 3.40 |
| | 3010 | -0.20 | 4.00 | 0.27 | 3.67 |
| | 3020 | 0.13 | 48.00 | 3.20 | 96.33 |
| | 3030 | 0.46 | 2.00 | 0.13 | 93.13 |
| | 3040 | 0.80 | 83.00 | 5.53 | 93.00 |
| | 3050 | 1.13 | 60.00 | 4.00 | 87.47 |
| | 3060 | 1.46 | 79.00 | 5.27 | 83.47 |
| | 3070 | 1.79 | 103.00 | 6.87 | 78.20 |
| | 3080 | 2.12 | 26.00 | 1.73 | 71.33 |
| | 3090 | 2.45 | 31.00 | 2.07 | 69.60 |
| | 3100 | 2.79 | 71.00 | 4.73 | 67.53 |
| | 3110 | 3.12 | 4.00 | 0.27 | 62.80 |
| | 3120 | 3.45 | 127.00 | 8.47 | 62.53 |
| | 3130 | 3.78 | 8.00 | 0.53 | 54.07 |
| | 3140 | 4.11 | 110.00 | 7.33 | 53.53 |
| | 3150 | 4.44 | 0.00 | 0.00 | 46.20 |
| | 3160 | 4.77 | 54.00 | 3.60 | 46.20 |
| | 3170 | 5.11 | 0.00 | 0.00 | 42.60 |
| | 3180 | 5.44 | 33.00 | 2.20 | 42.60 |
| | 3190 | 5.77 | 0.00 | 0.00 | 40.40 |
| | 3200 | 6.10 | 93.00 | 6.20 | 40.40 |

Table A.26 continued

| | | | | | |
|---|---|---|---|---|---|
| | 3210 | 6.43 | 0.00 | 0.00 | 34.20 |
| | 3220 | 6.76 | 84.00 | 5.60 | 34.20 |
| | 3230 | 7.10 | 0.00 | 0.00 | 28.60 |
| | 3240 | 7.43 | 56.00 | 3.73 | 28.60 |
| | 3250 | 7.76 | 0.00 | 0.00 | 24.87 |
| | 3260 | 8.09 | 114.00 | 7.60 | 24.87 |
| | 3270 | 8.42 | 0.00 | 0.00 | 17.27 |
| | 3280 | 8.75 | 79.00 | 5.27 | 17.27 |
| | 3290 | 9.08 | 0.00 | 0.00 | 12.00 |
| | 3300 | 9.42 | 68.00 | 4.53 | 12.00 |
| | 3310 | 9.75 | 0.00 | 0.00 | 7.47 |
| | 3320 | 10.08 | 32.00 | 2.13 | 7.47 |
| | 3330 | 10.41 | 0.00 | 0.00 | 5.33 |
| | 3340 | 10.74 | 57.00 | 3.80 | 5.33 |
| | 3350 | 11.07 | 0.00 | 0.00 | 1.53 |
| | 3360 | 11.41 | 23.00 | 1.53 | 1.53 |
| | | | | | |
| | | | 1500.00 | | |

Table A.27: Healthcare System 1; 5 years (0.75 Mean)

| Deterministic KWH | Probabilistic KWH | % Difference | Bin Size | % Probability | % Cumulative |
|---|---|---|---|---|---|
| 3016 | | | | | |
| | 3200 | 6.10 | 2.00 | 0.40 | 100.00 |
| | 3220 | 6.76 | 43.00 | 8.60 | 99.60 |
| | 3240 | 7.43 | 34.00 | 6.80 | 91.00 |
| | 3260 | 8.09 | 57.00 | 11.40 | 84.20 |
| | 3280 | 8.75 | 25.00 | 5.00 | 72.80 |
| | 3300 | 9.42 | 68.00 | 13.60 | 67.80 |
| | 3320 | 10.08 | 12.00 | 2.40 | 54.20 |
| | 3340 | 10.74 | 6.00 | 1.20 | 51.80 |
| | 3360 | 11.41 | 19.00 | 3.80 | 50.60 |
| | 3380 | 12.07 | 79.00 | 15.80 | 46.80 |
| | 3400 | 12.73 | 31.00 | 6.20 | 31.00 |
| | 3420 | 13.40 | 59.00 | 11.80 | 24.80 |
| | 3440 | 14.06 | 33.00 | 6.60 | 13.00 |
| | 3460 | 14.72 | 30.00 | 6.00 | 6.40 |
| | 3480 | 15.38 | 2.00 | 0.40 | 0.40 |
| | | | 500.00 | | |

Table A.28: Healthcare System 1; 5 years average

| Deterministic KWH | Probabilistic KWH | % Difference | Bin Size | % Probability | % Cumulative |
|---|---|---|---|---|---|
| 3016 | | | | | |
| | 3010 | -0.20 | 1.00 | 0.07 | 0.07 |
| | 3020 | 0.13 | 12.00 | 0.80 | 99.93 |
| | 3030 | 0.46 | 37.00 | 2.47 | 99.13 |
| | 3040 | 0.80 | 8.00 | 0.53 | 96.67 |
| | 3050 | 1.13 | 44.00 | 2.93 | 96.13 |
| | 3060 | 1.46 | 2.00 | 0.13 | 93.20 |
| | 3070 | 1.79 | 84.00 | 5.60 | 93.07 |
| | 3080 | 2.12 | 58.00 | 3.87 | 87.47 |
| | 3090 | 2.45 | 31.00 | 2.07 | 83.60 |
| | 3100 | 2.79 | 107.00 | 7.13 | 81.53 |
| | 3110 | 3.12 | 7.00 | 0.47 | 74.40 |
| | 3120 | 3.45 | 66.00 | 4.40 | 73.93 |
| | 3130 | 3.78 | 15.00 | 1.00 | 69.53 |
| | 3140 | 4.11 | 32.00 | 2.13 | 68.53 |
| | 3150 | 4.44 | 49.00 | 3.27 | 66.40 |
| | 3160 | 4.77 | 60.00 | 4.00 | 63.13 |
| | 3170 | 5.11 | 0.00 | 0.00 | 59.13 |
| | 3180 | 5.44 | 74.00 | 4.93 | 59.13 |
| | 3190 | 5.77 | 0.00 | 0.00 | 54.20 |
| | 3200 | 6.10 | 40.00 | 2.67 | 54.20 |
| | 3210 | 6.43 | 0 | 0.00 | 51.53 |
| | 3220 | 6.76 | 76 | 5.07 | 51.53 |
| | 3230 | 7.10 | 0 | 0.00 | 46.47 |
| | 3240 | 7.43 | 41 | 2.73 | 46.47 |
| | 3250 | 7.76 | 0 | 0.00 | 43.73 |
| | 3260 | 8.09 | 80 | 5.33 | 43.73 |
| | 3270 | 8.42 | 0 | 0.00 | 38.40 |
| | 3280 | 8.75 | 84 | 5.60 | 38.40 |
| | 3290 | 9.08 | 0 | 0.00 | 32.80 |
| | 3300 | 9.42 | 119 | 7.93 | 32.80 |
| | 3310 | 9.75 | 0 | 0.00 | 24.87 |
| | 3320 | 10.08 | 52 | 3.47 | 24.87 |
| | 3330 | 10.41 | 0 | 0.00 | 21.40 |
| | 3340 | 10.74 | 64 | 4.27 | 21.40 |
| | 3350 | 11.07 | 0 | 0.00 | 17.13 |
| | 3360 | 11.41 | 23 | 1.53 | 17.13 |

Table A.28 continued

| | | | | | |
|---|---|---|---|---|---|
| | 3370 | 11.74 | 0 | 0.00 | 15.60 |
| | 3380 | 12.07 | 79 | 5.27 | 15.60 |
| | 3390 | 12.40 | 0 | 0.00 | 10.33 |
| | 3400 | 12.73 | 31 | 2.07 | 10.33 |
| | 3410 | 13.06 | 0 | 0.00 | 8.27 |
| | 3420 | 13.40 | 59 | 3.93 | 8.27 |
| | 3430 | 13.73 | 0 | 0.00 | 4.33 |
| | 3440 | 14.06 | 33 | 2.20 | 4.33 |
| | 3450 | 14.39 | 0 | 0.00 | 2.13 |
| | 3460 | 14.72 | 30 | 2.00 | 2.13 |
| | 3470 | 15.05 | 0 | 0.00 | 0.13 |
| | 3480 | 15.38 | 2 | 0.13 | 0.13 |
| | | | | | |
| | | | 1500.00 | | |

Table A.29: Healthcare System 2; first year (0.75 Mean)

| Deterministic KWH | Probabilistic KWH | % Difference | Bin Size | % Probability | % Cumulative |
|---|---|---|---|---|---|
| 3912 | | | | | |
| | 4100 | 4.81 | 1.00 | 0.20 | 100.00 |
| | 4110 | 5.06 | 4.00 | 0.80 | 99.80 |
| | 4120 | 5.32 | 16.00 | 3.20 | 99.00 |
| | 4130 | 5.57 | 18.00 | 3.60 | 95.80 |
| | 4140 | 5.83 | 68.00 | 13.60 | 92.20 |
| | 4150 | 6.08 | 45.00 | 9.00 | 78.60 |
| | 4160 | 6.34 | 99.00 | 19.80 | 69.60 |
| | 4170 | 6.60 | 45.00 | 9.00 | 49.80 |
| | 4180 | 6.85 | 89.00 | 17.80 | 40.80 |
| | 4190 | 7.11 | 40.00 | 8.00 | 23.00 |
| | 4200 | 7.36 | 47.00 | 9.40 | 15.00 |
| | 4210 | 7.62 | 22.00 | 4.40 | 5.60 |
| | 4220 | 7.87 | 4.00 | 0.80 | 1.20 |
| | 4230 | 8.13 | 2.00 | 0.40 | 0.40 |
| | | | 500 | | |

Table A.30: Healthcare System 2; 1st year average

| Deterministic KWH | Probabilistic KWH | % Difference | Bin Size | % Probability | % Cumulative |
|---|---|---|---|---|---|
| 3912 | | | | | |
| | 3930 | 0.46 | 32.00 | 2.13 | 100.00 |
| | 3940 | 0.72 | 23.00 | 1.53 | 97.87 |
| | 3950 | 0.97 | 30.00 | 2.00 | 96.33 |
| | 3960 | 1.23 | 128.00 | 8.53 | 94.33 |
| | 3970 | 1.48 | 80.00 | 5.33 | 85.80 |
| | 3980 | 1.74 | 115.00 | 7.67 | 80.47 |
| | 3990 | 1.99 | 65.00 | 4.33 | 72.80 |
| | 4000 | 2.25 | 18.00 | 1.20 | 68.47 |
| | 4010 | 2.51 | 17.00 | 1.13 | 67.27 |
| | 4020 | 2.76 | 20.00 | 1.33 | 66.13 |
| | 4030 | 3.02 | 33.00 | 2.20 | 64.80 |
| | 4040 | 3.27 | 64.00 | 4.27 | 62.60 |
| | 4050 | 3.53 | 69.00 | 4.60 | 58.33 |
| | 4060 | 3.78 | 90.00 | 6.00 | 53.73 |
| | 4070 | 4.04 | 86.00 | 5.73 | 47.73 |
| | 4080 | 4.29 | 43.00 | 2.87 | 42.00 |
| | 4090 | 4.55 | 57.00 | 3.80 | 39.13 |
| | 4100 | 4.81 | 20.00 | 1.33 | 35.33 |
| | 4110 | 5.06 | 15.00 | 1.00 | 34.00 |
| | 4120 | 5.32 | 16.00 | 1.07 | 33.00 |
| | 4130 | 5.57 | 18.00 | 1.20 | 31.93 |
| | 4140 | 5.83 | 68.00 | 4.53 | 30.73 |
| | 4150 | 6.08 | 45.00 | 3.00 | 26.20 |
| | 4160 | 6.34 | 99.00 | 6.60 | 23.20 |
| | 4170 | 6.60 | 45.00 | 3.00 | 16.60 |
| | 4180 | 6.85 | 89.00 | 5.93 | 13.60 |
| | 4190 | 7.11 | 40.00 | 2.67 | 7.67 |
| | 4200 | 7.36 | 47.00 | 3.13 | 5.00 |
| | 4210 | 7.62 | 22.00 | 1.47 | 1.87 |
| | 4220 | 7.87 | 4.00 | 0.27 | 0.40 |
| | 4230 | 8.13 | 2.00 | 0.13 | 0.13 |
| | | | 1500.00 | | |

Table A.31: Healthcare System 2; 5 years (0.75 Mean)

| Deterministic KWH | Probabilistic KWH | % Difference | Bin Size | % Probability | % Cumulative |
|---|---|---|---|---|---|
| 3912 | | | | | |
| | 4230 | 8.13 | 4.00 | 0.80 | 100.00 |
| | 4240 | 8.38 | 10.00 | 2.00 | 99.20 |
| | 4250 | 8.64 | 11.00 | 2.20 | 97.20 |
| | 4260 | 8.90 | 25.00 | 5.00 | 95.00 |
| | 4270 | 9.15 | 80.00 | 16.00 | 90.00 |
| | 4280 | 9.41 | 59.00 | 11.80 | 74.00 |
| | 4290 | 9.66 | 51.00 | 10.20 | 62.20 |
| | 4300 | 9.92 | 117.00 | 23.40 | 52.00 |
| | 4310 | 10.17 | 44.00 | 8.80 | 28.60 |
| | 4320 | 10.43 | 31.00 | 6.20 | 19.80 |
| | 4330 | 10.69 | 51.00 | 10.20 | 13.60 |
| | 4340 | 10.94 | 8.00 | 1.60 | 3.40 |
| | 4350 | 11.20 | 7.00 | 1.40 | 1.80 |
| | 4360 | 11.45 | 1.00 | 0.20 | 0.40 |
| | 4370 | 11.71 | 1.00 | 0.20 | 0.20 |
| | | | 500.00 | | |

Table A.32: Healthcare System 2; 5 years average

| Deterministic KWH | Probabilistic KWH | % Difference | Bin Size | % Probability | % Cumulative |
|---|---|---|---|---|---|
| 3912 | | | | | |
| | 3960 | 1.23 | 2.00 | 0.13 | 100.00 |
| | 3970 | 1.48 | 29.00 | 1.93 | 99.87 |
| | 3980 | 1.74 | 42.00 | 2.80 | 97.93 |
| | 3990 | 1.99 | 37.00 | 2.47 | 95.13 |
| | 4000 | 2.25 | 112.00 | 7.47 | 92.67 |
| | 4010 | 2.51 | 95.00 | 6.33 | 85.20 |
| | 4020 | 2.76 | 126.00 | 8.40 | 78.87 |
| | 4030 | 3.02 | 30.00 | 2.00 | 70.47 |
| | 4040 | 3.27 | 16.00 | 1.07 | 68.47 |
| | 4050 | 3.53 | 11.00 | 0.73 | 67.40 |
| | 4060 | 3.78 | 0.00 | 0.00 | 66.67 |
| | 4070 | 4.04 | 0.00 | 0.00 | 66.67 |
| | 4080 | 4.29 | 0.00 | 0.00 | 66.67 |
| | 4090 | 4.55 | 14.00 | 0.93 | 66.67 |
| | 4100 | 4.81 | 18.00 | 1.20 | 65.73 |
| | 4110 | 5.06 | 45.00 | 3.00 | 64.53 |
| | 4120 | 5.32 | 35.00 | 2.33 | 61.53 |
| | 4130 | 5.57 | 77.00 | 5.13 | 59.20 |

Table A.32 continued

| | | | | | |
|---|---|---|---|---|---|
| | 4140 | 5.83 | 85.00 | 5.67 | 54.07 |
| | 4150 | 6.08 | 80.00 | 5.33 | 48.40 |
| | 4160 | 6.34 | 62 | 4.13 | 43.07 |
| | 4170 | 6.60 | 49 | 3.27 | 38.93 |
| | 4180 | 6.85 | 26 | 1.73 | 35.67 |
| | 4190 | 7.11 | 8 | 0.53 | 33.93 |
| | 4200 | 7.36 | 1 | 0.07 | 33.40 |
| | 4210 | 7.62 | 0 | 0.00 | 33.33 |
| | 4220 | 7.87 | 0 | 0.00 | 33.33 |
| | 4230 | 8.13 | 4 | 0.27 | 33.33 |
| | 4240 | 8.38 | 10 | 0.67 | 33.07 |
| | 4250 | 8.64 | 11 | 0.73 | 32.40 |
| | 4260 | 8.90 | 25 | 1.67 | 31.67 |
| | 4270 | 9.15 | 80 | 5.33 | 30.00 |
| | 4280 | 9.41 | 59 | 3.93 | 24.67 |
| | 4290 | 9.66 | 51 | 3.40 | 20.73 |
| | 4300 | 9.92 | 117 | 7.80 | 17.33 |
| | 4310 | 10.17 | 44 | 2.93 | 9.53 |
| | 4320 | 10.43 | 31 | 2.07 | 6.60 |
| | 4330 | 10.69 | 51 | 3.40 | 4.53 |

Table A.32 continued

| | | | | | |
|---|---|---|---|---|---|
| | 4340 | 10.94 | 8 | 0.53 | 1.13 |
| | 4350 | 11.20 | 7 | 0.47 | 0.60 |
| | 4360 | 11.45 | 1 | 0.07 | 0.13 |
| | 4370 | 11.71 | 1 | 0.07 | 0.07 |
| | | | 1500.00 | | |

Table A.33: Healthcare System 3; first year (0.75 Mean)

| Deterministic KWH | Probabilistic KWH | % Difference | Bin Size | % Probability | % Cumulative |
|---|---|---|---|---|---|
| 4169 | | | | | |
| | 3100 | -25.64 | 10.00 | 2.00 | 2.00 |
| | 4300 | 3.14 | 10.00 | 2.00 | 98.00 |
| | 4400 | 5.54 | 380.00 | 76.00 | 96.00 |
| | 4500 | 7.94 | 100.00 | 20.00 | 20.00 |
| | | | 500.00 | | |

Table A.34: Healthcare System 3; 1st year average

| Deterministic KWH | Probabilistic KWH | % Difference | Bin Size | % Probability | % Cumulative |
|---|---|---|---|---|---|
| 4169 | | | | | |
| | 3100 | -25.64 | 10.00 | 0.67 | 0.67 |
| | 4160 | -0.22 | 3.00 | 0.20 | 0.87 |
| | 4170 | 0.02 | 24.00 | 1.60 | 99.13 |
| | 4180 | 0.26 | 36.00 | 2.40 | 97.53 |
| | 4190 | 0.50 | 155.00 | 10.33 | 95.13 |
| | 4200 | 0.74 | 70.00 | 4.67 | 84.80 |
| | 4210 | 0.98 | 85.00 | 5.67 | 80.13 |
| | 4220 | 1.22 | 98.00 | 6.53 | 74.47 |
| | 4230 | 1.46 | 26.00 | 1.73 | 67.93 |
| | 4240 | 1.70 | 3.00 | 0.20 | 66.20 |
| | 4250 | 1.94 | 2.00 | 0.13 | 66.00 |
| | 4260 | 2.18 | 2.00 | 0.13 | 65.87 |
| | 4270 | 2.42 | 36.00 | 2.40 | 65.73 |
| | 4280 | 2.66 | 37.00 | 2.47 | 63.33 |
| | 4290 | 2.90 | 60.00 | 4.00 | 60.87 |
| | 4300 | 3.14 | 62.00 | 4.13 | 56.87 |
| | 4310 | 3.38 | 93.00 | 6.20 | 52.73 |
| | 4320 | 3.62 | 80.00 | 5.33 | 46.53 |
| | 4330 | 3.86 | 42.00 | 2.80 | 41.20 |
| | 4340 | 4.10 | 42.00 | 2.80 | 38.40 |
| | 4350 | 4.34 | 18.00 | 1.20 | 35.60 |
| | 4360 | 4.58 | 16.00 | 1.07 | 34.40 |
| | 4370 | 4.82 | 15.00 | 1.00 | 33.33 |
| | 4380 | 5.06 | 3.00 | 0.20 | 32.33 |
| | 4390 | 5.30 | 2.00 | 0.13 | 32.13 |
| | 4400 | 5.54 | 380.00 | 25.33 | 32.00 |
| | 4410 | 5.78 | 0.00 | 0.00 | 6.67 |
| | 4420 | 6.02 | 0.00 | 0.00 | 6.67 |
| | 4430 | 6.26 | 0.00 | 0.00 | 6.67 |
| | 4440 | 6.50 | 0.00 | 0.00 | 6.67 |
| | 4450 | 6.74 | 0.00 | 0.00 | 6.67 |
| | 4460 | 6.98 | 0.00 | 0.00 | 6.67 |
| | 4470 | 7.22 | 0.00 | 0.00 | 6.67 |
| | 4480 | 7.46 | 0.00 | 0.00 | 6.67 |
| | 4490 | 7.70 | 0.00 | 0.00 | 6.67 |
| | 4500 | 7.94 | 100.00 | 6.67 | 6.67 |
| | | | 1500.00 | | |

Table A.35: Healthcare System 3; 5 years (0.75 Mean)

| Deterministic KWH | Probabilistic KWH | % Difference | Bin Size | % Probability | % Cumulative |
|---|---|---|---|---|---|
| 4169 | | | | | |
| | 3200 | -23.24 | 5.00 | 1.00 | 1.00 |
| | 4500 | 7.94 | 45.00 | 9.00 | 99.00 |
| | 4600 | 10.34 | 450.00 | 90.00 | 90.00 |
| | | | 500.00 | | |

Table A.36: Healthcare System 3; 5 years average

| Deterministic KWH | Probabilistic KWH | % Difference | Bin Size | % Probability | % Cumulative |
|---|---|---|---|---|---|
| 4169 | | | | | |
| | 3200 | -23.24 | 5.00 | 0.33 | 0.33 |
| | 4200 | 0.74 | 3.00 | 0.20 | 99.67 |
| | 4210 | 0.98 | 18.00 | 1.20 | 99.47 |
| | 4220 | 1.22 | 30.00 | 2.00 | 98.27 |
| | 4230 | 1.46 | 58.00 | 3.87 | 96.27 |
| | 4240 | 1.70 | 175.00 | 11.67 | 92.40 |
| | 4250 | 1.94 | 68.00 | 4.53 | 80.73 |
| | 4260 | 2.18 | 62.00 | 4.13 | 76.20 |
| | 4270 | 2.42 | 76.00 | 5.07 | 72.07 |
| | 4280 | 2.66 | 10.00 | 0.67 | 67.00 |
| | 4290 | 2.90 | 0.00 | 0.00 | 66.33 |
| | 4300 | 3.14 | 0.00 | 0.00 | 66.33 |
| | 4310 | 3.38 | 0.00 | 0.00 | 66.33 |
| | 4320 | 3.62 | 0.00 | 0.00 | 66.33 |
| | 4330 | 3.86 | 1.00 | 0.07 | 66.33 |
| | 4340 | 4.10 | 1.00 | 0.07 | 66.27 |
| | 4350 | 4.34 | 4.00 | 0.27 | 66.20 |
| | 4360 | 4.58 | 40.00 | 2.67 | 65.93 |
| | 4370 | 4.82 | 69.00 | 4.60 | 63.27 |
| | 4380 | 5.06 | 49.00 | 3.27 | 58.67 |
| | 4390 | 5.30 | 46 | 3.07 | 55.40 |
| | 4400 | 5.54 | 104 | 6.93 | 52.33 |
| | 4410 | 5.78 | 74 | 4.93 | 45.40 |
| | 4420 | 6.02 | 33 | 2.20 | 40.47 |
| | 4430 | 6.26 | 19 | 1.27 | 38.27 |
| | 4440 | 6.50 | 28 | 1.87 | 37.00 |
| | 4450 | 6.74 | 9 | 0.60 | 35.13 |
| | 4460 | 6.98 | 17 | 1.13 | 34.53 |
| | 4470 | 7.22 | 4 | 0.27 | 33.40 |
| | 4480 | 7.46 | 2 | 0.13 | 33.13 |
| | 4490 | 7.70 | 0 | 0.00 | 33.00 |

Table A.36 continued

| | | | | | |
|---|---|---|---|---|---|
| | 4500 | 7.94 | 45 | 3.00 | 33.00 |
| | 4510 | 8.18 | 0 | 0.00 | 30.00 |
| | 4520 | 8.42 | 0 | 0.00 | 30.00 |
| | 4530 | 8.66 | 0 | 0.00 | 30.00 |
| | 4540 | 8.90 | 0 | 0.00 | 30.00 |
| | 4550 | 9.14 | 0 | 0.00 | 30.00 |
| | 4560 | 9.38 | 0 | 0.00 | 30.00 |
| | 4570 | 9.62 | 0 | 0.00 | 30.00 |
| | 4580 | 9.86 | 0 | 0.00 | 30.00 |
| | 4590 | 10.10 | 0 | 0.00 | 30.00 |
| | 4600 | 10.34 | 450 | 30.00 | 30.00 |
| | | | 1500.00 | | |

Table A.37: Healthcare System 4; first year (0.75 Mean)

| Deterministic KWH | Probabilistic KWH | % Difference | Bin Size | % Probability | % Cumulative |
|---|---|---|---|---|---|
| 3881 | | | | | |
| | 4040 | 4.10 | 19.00 | 3.80 | 100.00 |
| | 4060 | 4.61 | 38.00 | 7.60 | 96.20 |
| | 4080 | 5.13 | 44.00 | 8.80 | 88.60 |
| | 4100 | 5.64 | 17.00 | 3.40 | 79.80 |
| | 4120 | 6.16 | 66.00 | 13.20 | 76.40 |
| | 4140 | 6.67 | 35.00 | 7.00 | 63.20 |
| | 4160 | 7.19 | 52.00 | 10.40 | 56.20 |
| | 4180 | 7.70 | 65.00 | 13.00 | 45.80 |
| | 4200 | 8.22 | 60.00 | 12.00 | 32.80 |
| | 4220 | 8.73 | 56.00 | 11.20 | 20.80 |
| | 4240 | 9.25 | 46.00 | 9.20 | 9.60 |
| | 4260 | 9.77 | 2.00 | 0.40 | 0.40 |
| | | | 500.00 | | |

Table A.38: Healthcare System 4; first year average

| Deterministic KWH | Probabilistic KWH | % Difference | Bin Size | % Probability | % Cumulative |
|---|---|---|---|---|---|
| 3881 | | | | | |
| | 3860 | -0.54 | 9.00 | 0.60 | 0.60 |
| | 3870 | -0.28 | 65.00 | 4.33 | 4.93 |
| | 3880 | -0.03 | 16.00 | 1.07 | 6.00 |
| | 3890 | 0.23 | 37.00 | 2.47 | 94.00 |
| | 3900 | 0.49 | 39.00 | 2.60 | 91.53 |
| | 3910 | 0.75 | 11.00 | 0.73 | 88.93 |
| | 3920 | 1.00 | 41.00 | 2.73 | 88.20 |
| | 3930 | 1.26 | 88.00 | 5.87 | 85.47 |
| | 3940 | 1.52 | 43.00 | 2.87 | 79.60 |
| | 3950 | 1.78 | 135.00 | 9.00 | 76.73 |
| | 3960 | 2.04 | 18.00 | 1.20 | 67.73 |
| | 3970 | 2.29 | 0.00 | 0.00 | 66.53 |
| | 3980 | 2.55 | 0.00 | 0.00 | 66.53 |
| | 3990 | 2.81 | 0.00 | 0.00 | 66.53 |
| | 4000 | 3.07 | 0.00 | 0.00 | 66.53 |
| | 4010 | 3.32 | 0.00 | 0.00 | 66.53 |
| | 4020 | 3.58 | 1.00 | 0.07 | 66.53 |
| | 4030 | 3.84 | 0.00 | 0.00 | 66.47 |
| | 4040 | 4.10 | 19.00 | 1.27 | 66.47 |
| | 4050 | 4.35 | 0.00 | 0.00 | 65.20 |
| | 4060 | 4.61 | 42.00 | 2.80 | 65.20 |
| | 4070 | 4.87 | 0.00 | 0.00 | 62.40 |
| | 4080 | 5.13 | 77.00 | 5.13 | 62.40 |
| | 4090 | 5.39 | 0.00 | 0.00 | 57.27 |
| | 4100 | 5.64 | 92.00 | 6.13 | 57.27 |
| | 4110 | 5.90 | 0.00 | 0.00 | 51.13 |
| | 4120 | 6.16 | 197.00 | 13.13 | 51.13 |
| | 4130 | 6.42 | 0.00 | 0.00 | 38.00 |
| | 4140 | 6.67 | 70.00 | 4.67 | 38.00 |
| | 4150 | 6.93 | 0.00 | 0.00 | 33.33 |
| | 4160 | 7.19 | 138.00 | 9.20 | 33.33 |
| | 4170 | 7.45 | 0.00 | 0.00 | 24.13 |
| | 4180 | 7.70 | 185.00 | 12.33 | 24.13 |

Table A.38 continued

| | | | | | |
|---|---|---|---|---|---|
| | 4190 | 7.96 | 0.00 | 0.00 | 11.80 |
| | 4200 | 8.22 | 73.00 | 4.87 | 11.80 |
| | 4210 | 8.48 | 0.00 | 0.00 | 6.93 |
| | 4220 | 8.73 | 56.00 | 3.73 | 6.93 |
| | 4230 | 8.99 | 0.00 | 0.00 | 3.20 |
| | 4240 | 9.25 | 46.00 | 3.07 | 3.20 |
| | 4250 | 9.51 | 0.00 | 0.00 | 0.13 |
| | 4260 | 9.77 | 2.00 | 0.13 | 0.13 |
| | | | 1500.00 | | |

Table A.39: Healthcare System 4; 5 years (0.75 Mean)

| Deterministic KWH | Probabilistic KWH | % Difference | Bin Size | % Probability | % Cumulative |
|---|---|---|---|---|---|
| 3881 | | | | | |
| | 4140 | 6.67 | 2.00 | 0.40 | 100.00 |
| | 4160 | 7.19 | 7.00 | 1.40 | 99.60 |
| | 4180 | 7.70 | 38.00 | 7.60 | 98.20 |
| | 4200 | 8.22 | 45.00 | 9.00 | 90.60 |
| | 4220 | 8.73 | 18.00 | 3.60 | 81.60 |
| | 4240 | 9.25 | 58.00 | 11.60 | 78.00 |
| | 4260 | 9.77 | 44.00 | 8.80 | 66.40 |
| | 4280 | 10.28 | 24.00 | 4.80 | 57.60 |
| | 4300 | 10.80 | 59.00 | 11.80 | 52.80 |
| | 4320 | 11.31 | 62.00 | 12.40 | 41.00 |
| | 4340 | 11.83 | 30.00 | 6.00 | 28.60 |
| | 4360 | 12.34 | 68.00 | 13.60 | 22.60 |
| | 4380 | 12.86 | 41.00 | 8.20 | 9.00 |
| | 4400 | 13.37 | 4.00 | 0.80 | 0.80 |
| | | | | | |
| | | | 500.00 | | |

Table A.40: Healthcare System 4; 5 years (average)

| Deterministic KWH | Probabilistic KWH | % Difference | Bin Size | % Probability | % Cumulative |
|---|---|---|---|---|---|
| 3881 | | | | | |
| | 3890 | 0.23 | 2.00 | 0.13 | 100.00 |
| | 3900 | 0.49 | 18.00 | 1.20 | 99.87 |
| | 3910 | 0.75 | 52.00 | 3.47 | 98.67 |
| | 3920 | 1.00 | 22.00 | 1.47 | 95.20 |
| | 3930 | 1.26 | 50.00 | 3.33 | 93.73 |
| | 3940 | 1.52 | 20.00 | 1.33 | 90.40 |
| | 3950 | 1.78 | 21.00 | 1.40 | 89.07 |
| | 3960 | 2.04 | 95.00 | 6.33 | 87.67 |
| | 3970 | 2.29 | 50.00 | 3.33 | 81.33 |
| | 3980 | 2.55 | 105.00 | 7.00 | 78.00 |
| | 3990 | 2.81 | 62.00 | 4.13 | 71.00 |
| | 4000 | 3.07 | 4.00 | 0.27 | 66.87 |
| | 4010 | 3.32 | 0.00 | 0.00 | 66.60 |
| | 4020 | 3.58 | 1.00 | 0.07 | 66.60 |
| | 4030 | 3.84 | 0.00 | 0.00 | 66.53 |
| | 4040 | 4.10 | 0.00 | 0.00 | 66.53 |
| | 4050 | 4.35 | 0.00 | 0.00 | 66.53 |
| | 4060 | 4.61 | 0.00 | 0.00 | 66.53 |
| | 4070 | 4.87 | 0.00 | 0.00 | 66.53 |
| | 4080 | 5.13 | 0.00 | 0.00 | 66.53 |
| | 4090 | 5.39 | 0 | 0.00 | 66.53 |
| | 4100 | 5.64 | 1 | 0.07 | 66.53 |
| | 4110 | 5.90 | 0 | 0.00 | 66.47 |
| | 4120 | 6.16 | 0 | 0.00 | 66.47 |
| | 4130 | 6.42 | 0 | 0.00 | 66.47 |
| | 4140 | 6.67 | 2 | 0.13 | 66.47 |
| | 4150 | 6.93 | 0 | 0.00 | 66.33 |
| | 4160 | 7.19 | 33 | 2.20 | 66.33 |
| | 4170 | 7.45 | 0 | 0.00 | 64.13 |
| | 4180 | 7.70 | 105 | 7.00 | 64.13 |
| | 4190 | 7.96 | 0 | 0.00 | 57.13 |
| | 4200 | 8.22 | 175 | 11.67 | 57.13 |

Table A.40 continued

| | | | | | |
|---|---|---|---|---|---|
| | 4210 | 8.48 | 0 | 0.00 | 45.47 |
| | 4220 | 8.73 | 76 | 5.07 | 45.47 |
| | 4230 | 8.99 | 0 | 0.00 | 40.40 |
| | 4240 | 9.25 | 130 | 8.67 | 40.40 |
| | 4250 | 9.51 | 0 | 0.00 | 31.73 |
| | 4260 | 9.77 | 167 | 11.13 | 31.73 |
| | 4270 | 10.02 | 0 | 0.00 | 20.60 |
| | 4280 | 10.28 | 44 | 2.93 | 20.60 |
| | 4290 | 10.54 | 0 | 0.00 | 17.67 |
| | 4300 | 10.80 | 60 | 4.00 | 17.67 |
| | 4310 | 11.05 | 0 | 0.00 | 13.67 |
| | 4320 | 11.31 | 62 | 4.13 | 13.67 |
| | 4330 | 11.57 | 0 | 0.00 | 9.53 |
| | 4340 | 11.83 | 30 | 2.00 | 9.53 |
| | 4350 | 12.08 | 0 | 0.00 | 7.53 |
| | 4360 | 12.34 | 68 | 4.53 | 7.53 |
| | 4370 | 12.60 | 0 | 0.00 | 3.00 |
| | 4380 | 12.86 | 41.00 | 2.73 | 3.00 |
| | 4390 | 13.12 | 0.00 | 0.00 | 0.27 |
| | 4400 | 13.37 | 4.00 | 0.27 | 0.27 |
| | | | 1500.00 | | |

Table A.41: Healthcare System 5; first year (0.75 Mean)

| Deterministic KWH | Probabilistic KWH | % Difference | Bin Size | % Probability | % Cumulative |
|---|---|---|---|---|---|
| 2564 | | | | | |
| | 2560 | -0.16 | 30.00 | 6.00 | 6.00 |
| | 2580 | 0.62 | 91.00 | 18.20 | 94.00 |
| | 2600 | 1.40 | 17.00 | 3.40 | 75.80 |
| | 2620 | 2.18 | 62.00 | 12.40 | 72.40 |
| | 2640 | 2.96 | 59.00 | 11.80 | 60.00 |
| | 2660 | 3.74 | 0.00 | 0.00 | 48.20 |
| | 2680 | 4.52 | 3.00 | 0.60 | 48.20 |
| | 2700 | 5.30 | 15.00 | 3.00 | 47.60 |
| | 2720 | 6.08 | 81.00 | 16.20 | 44.60 |
| | 2740 | 6.86 | 18.00 | 3.60 | 28.40 |
| | 2760 | 7.64 | 88.00 | 17.60 | 24.80 |
| | 2780 | 8.42 | 36.00 | 7.20 | 7.20 |
| | | | 500 | | |

Table A.42: Healthcare System 5; first year average

| Deterministic KWH | Probabilistic KWH | % Difference | Bin Size | % Probability | % Cumulative |
|---|---|---|---|---|---|
| 2564 | | | | | |
| | 2470 | -3.67 | 2.00 | 0.13 | 0.13 |
| | 2480 | -3.28 | 102.00 | 6.80 | 6.93 |
| | 2490 | -2.89 | 17.00 | 1.13 | 8.07 |
| | 2500 | -2.50 | 0.00 | 0.00 | 8.07 |
| | 2510 | -2.11 | 0.00 | 0.00 | 8.07 |
| | 2520 | -1.72 | 46.00 | 3.07 | 11.13 |
| | 2530 | -1.33 | 221.00 | 14.73 | 25.87 |
| | 2540 | -0.94 | 137.00 | 9.13 | 35.00 |
| | 2550 | -0.55 | 0.00 | 0.00 | 35.00 |
| | 2560 | -0.16 | 40.00 | 2.67 | 37.67 |
| | 2570 | 0.23 | 40.00 | 2.67 | 62.33 |
| | 2580 | 0.62 | 227.00 | 15.13 | 59.67 |
| | 2590 | 1.01 | 12.00 | 0.80 | 44.53 |
| | 2600 | 1.40 | 33.00 | 2.20 | 43.73 |
| | 2610 | 1.79 | 0.00 | 0.00 | 41.53 |
| | 2620 | 2.18 | 75.00 | 5.00 | 41.53 |
| | 2630 | 2.57 | 0.00 | 0.00 | 36.53 |
| | 2640 | 2.96 | 59.00 | 3.93 | 36.53 |
| | 2650 | 3.35 | 0.00 | 0.00 | 32.60 |
| | 2660 | 3.74 | 38.00 | 2.53 | 32.60 |
| | 2670 | 4.13 | 0.00 | 0.00 | 30.07 |

Table A.42 continued

| | | | | | |
|---|---|---|---|---|---|
| | 2680 | 4.52 | 102.00 | 6.80 | 30.07 |
| | 2690 | 4.91 | 0.00 | 0.00 | 23.27 |
| | 2700 | 5.30 | 19.00 | 1.27 | 23.27 |
| | 2710 | 5.69 | 0.00 | 0.00 | 22.00 |
| | 2720 | 6.08 | 121.00 | 8.07 | 22.00 |
| | 2730 | 6.47 | 0.00 | 0.00 | 13.93 |
| | 2740 | 6.86 | 85.00 | 5.67 | 13.93 |
| | 2750 | 7.25 | 0.00 | 0.00 | 8.27 |
| | 2760 | 7.64 | 88.00 | 5.87 | 8.27 |
| | 2770 | 8.03 | 0.00 | 0.00 | 2.40 |
| | 2780 | 8.42 | 36.00 | 2.40 | 2.40 |
| | | | 1500.00 | | |

Table A.43: Healthcare System 5; 5 years (0.75 Mean)

| Deterministic KWH | Probabilistic KWH | % Difference | Bin Size | % Probability | % Cumulative |
|---|---|---|---|---|---|
| 2564 | | | | | |
| | 2620 | 2.18 | 3.00 | 0.60 | 100.00 |
| | 2640 | 2.96 | 65.00 | 13.00 | 99.40 |
| | 2660 | 3.74 | 46.00 | 9.20 | 86.40 |
| | 2680 | 4.52 | 25.00 | 5.00 | 77.20 |
| | 2700 | 5.30 | 107.00 | 21.40 | 72.20 |
| | 2720 | 6.08 | 12.00 | 2.40 | 50.80 |
| | 2740 | 6.86 | 0.00 | 0.00 | 48.40 |
| | 2760 | 7.64 | 5.00 | 1.00 | 48.40 |
| | 2780 | 8.42 | 21.00 | 4.20 | 47.40 |
| | 2800 | 9.20 | 76.00 | 15.20 | 43.20 |
| | 2820 | 9.98 | 31.00 | 6.20 | 28.00 |
| | 2840 | 10.76 | 53.00 | 10.60 | 21.80 |
| | 2860 | 11.54 | 54.00 | 10.80 | 11.20 |
| | 2880 | 12.32 | 2.00 | 0.40 | 0.40 |
| | | | 500.00 | | |

Table A.44: Healthcare System 5; 5 years average

| Deterministic KWH | Probabilistic KWH | % Difference | Bin Size | % Probability | % Cumulative |
|---|---|---|---|---|---|
| 2564 | | | | | |
| | 2490 | -2.89 | 1.00 | 0.07 | 0.07 |
| | 2500 | -2.50 | 104.00 | 6.93 | 7.00 |
| | 2510 | -2.11 | 17.00 | 1.13 | 8.13 |
| | 2520 | -1.72 | 0.00 | 0.00 | 8.13 |
| | 2530 | -1.33 | 0.00 | 0.00 | 8.13 |
| | 2540 | -0.94 | 1.00 | 0.07 | 8.20 |
| | 2550 | -0.55 | 161.00 | 10.73 | 18.93 |
| | 2560 | -0.16 | 122.00 | 8.13 | 27.07 |
| | 2570 | 0.23 | 0.00 | 0.00 | 72.93 |
| | 2580 | 0.62 | 110.00 | 7.33 | 72.93 |
| | 2590 | 1.01 | 16.00 | 1.07 | 65.60 |
| | 2600 | 1.40 | 42.00 | 2.80 | 64.53 |
| | 2610 | 1.79 | 46.00 | 3.07 | 61.73 |
| | 2620 | 2.18 | 29.00 | 1.93 | 58.67 |
| | 2630 | 2.57 | 0.00 | 0.00 | 56.73 |
| | 2640 | 2.96 | 156.00 | 10.40 | 56.73 |
| | 2650 | 3.35 | 0.00 | 0.00 | 46.33 |
| | 2660 | 3.74 | 50.00 | 3.33 | 46.33 |
| | 2670 | 4.13 | 0.00 | 0.00 | 43.00 |
| | 2680 | 4.52 | 35.00 | 2.33 | 43.00 |
| | 2690 | 4.91 | 0 | 0.00 | 40.67 |
| | 2700 | 5.30 | 115 | 7.67 | 40.67 |
| | 2710 | 5.69 | 0 | 0.00 | 33.00 |
| | 2720 | 6.08 | 62 | 4.13 | 33.00 |
| | 2730 | 6.47 | 0 | 0.00 | 28.87 |
| | 2740 | 6.86 | 78 | 5.20 | 28.87 |
| | 2750 | 7.25 | 0 | 0.00 | 23.67 |
| | 2760 | 7.64 | 23 | 1.53 | 23.67 |
| | 2770 | 8.03 | 0 | 0.00 | 22.13 |
| | 2780 | 8.42 | 80 | 5.33 | 22.13 |
| | 2790 | 8.81 | 0 | 0.00 | 16.80 |
| | 2800 | 9.20 | 112 | 7.47 | 16.80 |
| | 2810 | 9.59 | 0 | 0.00 | 9.33 |

Table A.44 continued

| | | | | | |
|---|---|---|---|---|---|
| | 2820 | 9.98 | 31 | 2.07 | 9.33 |
| | 2830 | 10.37 | 0 | 0.00 | 7.27 |
| | 2840 | 10.76 | 53 | 3.53 | 7.27 |
| | 2850 | 11.15 | 0 | 0.00 | 3.73 |
| | 2860 | 11.54 | 54 | 3.60 | 3.73 |
| | 2870 | 11.93 | 0 | 0.00 | 0.13 |
| | 2880 | 12.32 | 2 | 0.13 | 0.13 |
| | | | 1500.00 | | |

Table A.45: Healthcare System 6; first year (0.75 Mean)

| Deterministic KWH | Probabilistic KWH | % Difference | Bin Size | % Probability | % Cumulative |
|---|---|---|---|---|---|
| 3503 | | | | | |
| | 3540 | 1.06 | 4.00 | 0.80 | 0.80 |
| | 3550 | 1.34 | 5.00 | 1.00 | 99.20 |
| | 3560 | 1.63 | 37.00 | 7.40 | 98.20 |
| | 3570 | 1.91 | 57.00 | 11.40 | 90.80 |
| | 3580 | 2.20 | 16.00 | 3.20 | 79.40 |
| | 3590 | 2.48 | 111.00 | 22.20 | 76.20 |
| | 3600 | 2.77 | 106.00 | 21.20 | 54.00 |
| | 3610 | 3.05 | 48.00 | 9.60 | 32.80 |
| | 3620 | 3.34 | 59.00 | 11.80 | 23.20 |
| | 3630 | 3.63 | 42.00 | 8.40 | 11.40 |
| | 3640 | 3.91 | 3.00 | 0.60 | 3.00 |
| | 3650 | 4.20 | 12.00 | 2.40 | 2.40 |
| | | | 500 | | |

Table A.46: Healthcare System 6; first year average

| Deterministic KWH | Probabilistic KWH | % Difference | Bin Size | % Probability | % Cumulative |
|---|---|---|---|---|---|
| 3503 | | | | | |
| | 3410 | -2.65 | 1.00 | 0.07 | 0.07 |
| | 3420 | -2.37 | 118.00 | 7.87 | 7.93 |
| | 3430 | -2.08 | 12.00 | 0.80 | 8.73 |
| | 3440 | -1.80 | 252.00 | 16.80 | 25.53 |
| | 3450 | -1.51 | 47.00 | 3.13 | 28.67 |
| | 3460 | -1.23 | 51.00 | 3.40 | 32.07 |
| | 3470 | -0.94 | 21.00 | 1.40 | 33.47 |
| | 3480 | -0.66 | 7.00 | 0.47 | 33.93 |
| | 3490 | -0.37 | 25.00 | 1.67 | 35.60 |
| | 3500 | -0.09 | 101.00 | 6.73 | 42.33 |
| | 3510 | 0.20 | 98.00 | 6.53 | 57.67 |
| | 3520 | 0.49 | 70.00 | 4.67 | 51.13 |
| | 3530 | 0.77 | 117.00 | 7.80 | 46.47 |
| | 3540 | 1.06 | 48.00 | 3.20 | 38.67 |
| | 3550 | 1.34 | 35.00 | 2.33 | 35.47 |
| | 3560 | 1.63 | 43.00 | 2.87 | 33.13 |
| | 3570 | 1.91 | 57.00 | 3.80 | 30.27 |
| | 3580 | 2.20 | 16.00 | 1.07 | 26.47 |
| | 3590 | 2.48 | 111.00 | 7.40 | 25.40 |
| | 3600 | 2.77 | 106.00 | 7.07 | 18.00 |
| | 3610 | 3.05 | 48.00 | 3.20 | 10.93 |
| | 3620 | 3.34 | 59.00 | 3.93 | 7.73 |
| | 3630 | 3.63 | 42.00 | 2.80 | 3.80 |
| | 3640 | 3.91 | 3.00 | 0.20 | 1.00 |
| | 3650 | 4.20 | 12.00 | 0.80 | 0.80 |
| | | | 1500.00 | | |

Table A.47: Healthcare System 6; 5 years (0.75 Mean)

| Deterministic KWH | Probabilistic KWH | % Difference | Bin Size | % Probability | % Cumulative |
|---|---|---|---|---|---|
| 3503 | | | | | |
| | 3650 | 4.20 | 14.00 | 2.80 | 100.00 |
| | 3660 | 4.48 | 13.00 | 2.60 | 97.20 |
| | 3670 | 4.77 | 42.00 | 8.40 | 94.60 |
| | 3680 | 5.05 | 28.00 | 5.60 | 86.20 |
| | 3690 | 5.34 | 79.00 | 15.80 | 80.60 |
| | 3700 | 5.62 | 46.00 | 9.20 | 64.80 |
| | 3710 | 5.91 | 113.00 | 22.60 | 55.60 |
| | 3720 | 6.19 | 46.00 | 9.20 | 33.00 |
| | 3730 | 6.48 | 66.00 | 13.20 | 23.80 |
| | 3740 | 6.77 | 27.00 | 5.40 | 10.60 |
| | 3750 | 7.05 | 16.00 | 3.20 | 5.20 |
| | 3760 | 7.34 | 10.00 | 2.00 | 2.00 |
| | | | 500.00 | | |

Table A.48: Healthcare System 6; 5 years (average)

| Deterministic KWH | Probabilistic KWH | % Difference | Bin Size | % Probability | % Cumulative |
|---|---|---|---|---|---|
| 3503 | | | | | |
| | 3450 | -1.51 | 25.00 | 1.67 | 1.67 |
| | 3460 | -1.23 | 104.00 | 6.93 | 8.60 |
| | 3470 | -0.94 | 30.00 | 2.00 | 10.60 |
| | 3480 | -0.66 | 235.00 | 15.67 | 26.27 |
| | 3490 | -0.37 | 43.00 | 2.87 | 29.13 |
| | 3500 | -0.09 | 50.00 | 3.33 | 32.47 |
| | 3510 | 0.20 | 13.00 | 0.87 | 33.33 |
| | 3520 | 0.49 | 0.00 | 0.00 | 33.33 |
| | 3530 | 0.77 | 0.00 | 0.00 | 66.67 |
| | 3540 | 1.06 | 5.00 | 0.33 | 66.67 |
| | 3550 | 1.34 | 14.00 | 0.93 | 66.33 |
| | 3560 | 1.63 | 33.00 | 2.20 | 65.40 |

Table A.48 continued

| | | | | | |
|---|---|---|---|---|---|
| | 3570 | 1.91 | 37.00 | 2.47 | 63.20 |
| | 3580 | 2.20 | 102.00 | 6.80 | 60.73 |
| | 3590 | 2.48 | 76.00 | 5.07 | 53.93 |
| | 3600 | 2.77 | 134.00 | 8.93 | 48.87 |
| | 3610 | 3.05 | 53.00 | 3.53 | 39.93 |
| | 3620 | 3.34 | 35.00 | 2.33 | 36.40 |
| | 3630 | 3.63 | 9.00 | 0.60 | 34.07 |
| | 3640 | 3.91 | 2.00 | 0.13 | 33.47 |
| | 3650 | 4.20 | 14 | 0.93 | 33.33 |
| | 3660 | 4.48 | 13 | 0.87 | 32.40 |
| | 3670 | 4.77 | 42 | 2.80 | 31.53 |
| | 3680 | 5.05 | 28 | 1.87 | 28.73 |
| | 3690 | 5.34 | 79 | 5.27 | 26.87 |
| | 3700 | 5.62 | 46 | 3.07 | 21.60 |

Table A.48 continued

| | | | | | |
|---|---|---|---|---|---|
| | 3710 | 5.91 | 113 | 7.53 | 18.53 |
| | 3720 | 6.19 | 46 | 3.07 | 11.00 |
| | 3730 | 6.48 | 66 | 4.40 | 7.93 |
| | 3740 | 6.77 | 27 | 1.80 | 3.53 |
| | 3750 | 7.05 | 16 | 1.07 | 1.73 |
| | 3760 | 7.34 | 10 | 0.67 | 0.67 |
| | | | 1500.00 | | |

Table A.49: Office System 1A; Sensitivity Analysis results

| System_1A_Component | 75% bin | 50% bin | 25% bin | Average bin |
|---|---|---|---|---|
| Supply Fan | 12 | 12 | 8 | 10.67 |
| Duct Air Leak | 4 | 11 | 17 | 10.67 |
| Chiller | 12 | 8 | 8 | 9.33 |
| Condenser Water Pump | 12 | 5 | 10 | 9.00 |
| Return Fan | 7 | 8 | 5 | 6.67 |
| Chilled Water Pump age | 5 | 10 | 3 | 6.00 |
| Cooling Tower age | 10 | 4 | 3 | 5.67 |
| Chilled Water Pump | 3 | 5 | 9 | 5.67 |
| Cooling Tower | 14 | 1 | 1 | 5.33 |
| Chiller age | 2 | 2 | 12 | 5.33 |
| Terminal Unit age | 5 | 11 | 0 | 5.33 |
| Return Fan age | 4 | 5 | 5 | 4.67 |
| Condenser Water Pump age | 3 | 5 | 6 | 4.67 |
| Terminal Unit | 0 | 5 | 9 | 4.67 |
| Load | 2 | 4 | 1 | 2.33 |
| Coil | 0 | 4 | 1 | 1.67 |
| Supply Fan age | 2 | 1 | 2 | 1.67 |

Table A.50: Office System 1B; Sensitivity Analysis results

| System_1B_Component | 75% bin | 50% bin | 25% bin | Average bin |
|---|---|---|---|---|
| Cooling Tower | 14 | 13 | 5 | 10.67 |
| Load | 10 | 4 | 12 | 8.67 |
| Return Fan age | 7 | 12 | 5 | 8.00 |
| Chilled Water Pump | 3 | 13 | 8 | 8.00 |
| Chilled Water Pump age | 7 | 15 | 1 | 7.67 |
| Chiller age | 6 | 3 | 13 | 7.33 |
| Terminal Unit | 0 | 6 | 12 | 6.00 |
| Supply Fan age | 6 | 6 | 3 | 5.00 |
| Duct Air Leak | 4 | 1 | 10 | 5.00 |
| Supply Fan | 2 | 5 | 7 | 4.67 |
| Terminal Unit age | 7 | 1 | 6 | 4.67 |
| Cooling Tower age | 5 | 3 | 6 | 4.67 |
| Condenser Water Pump age | 1 | 10 | 3 | 4.67 |
| Coil | 4 | 4 | 5 | 4.33 |
| Chiller | 9 | 2 | 0 | 3.67 |
| Condenser Water Pump | 9 | 1 | 1 | 3.67 |
| Return Fan | 2 | 3 | 2 | 2.33 |

# APPENDIX B

# BEFORE AND AFTER IMPROVEMENT COMPARISON

Table B.1: Office System 1, before and after improvement

| Energy Consumption kwh | Bin size after Improvement | Bin size before Improvement | Total EC After | Total EC Before | Net Difference |
|---|---|---|---|---|---|
| 2900 | 4 | 0 | 11600 | 0 | |
| 2910 | 20 | 0 | 58200 | 0 | |
| 2920 | 46 | 0 | 134320 | 0 | |
| 2930 | 75 | 0 | 219750 | 0 | |
| 2940 | 6 | 124 | 17640 | 364560 | |
| 2950 | 37 | 0 | 109150 | 0 | |
| 2960 | 110 | 132 | 325600 | 390720 | |
| 2970 | 118 | 0 | 350460 | 0 | |
| 2980 | 128 | 147 | 381440 | 438060 | |
| 2990 | 67 | 0 | 200330 | 0 | |
| 3000 | 36 | 108 | 108000 | 324000 | |
| 3010 | 113 | 0 | 340130 | 0 | |
| 3020 | 95 | 121 | 286900 | 365420 | |
| 3030 | 82 | 0 | 248460 | 0 | |
| 3040 | 75 | 81 | 228000 | 246240 | |
| 3050 | 28 | 0 | 85400 | 0 | |
| 3060 | 107 | 97 | 327420 | 296820 | |
| 3070 | 30 | 0 | 92100 | 0 | |
| 3080 | 150 | 49 | 462000 | 150920 | |
| 3090 | 5 | 0 | 15450 | 0 | |
| 3100 | 33 | 51 | 102300 | 158100 | |
| 3110 | 0 | 0 | 0 | 0 | |
| 3120 | 64 | 123 | 199680 | 383760 | |
| 3130 | 0 | 0 | 0 | 0 | |
| 3140 | 60 | 77 | 188400 | 241780 | |
| 3150 | 0 | 0 | 0 | 0 | |
| 3160 | 6 | 84 | 18960 | 265440 | |
| 3170 | 0 | 0 | 0 | 0 | |
| 3180 | 3 | 103 | 9540 | 327540 | |
| 3190 | 0 | 0 | 0 | 0 | |
| 3200 | 0 | 70 | 0 | 224000 | |
| 3210 | 0 | 0 | 0 | 0 | |
| 3220 | 2 | 37 | 6440 | 119140 | |
| 3230 | 0 | 0 | 0 | 0 | |

Table B.1 continued

| | | | | | |
|---|---|---|---|---|---|
| 3240 | 0 | 85 | 0 | 275400 | |
| 3250 | 0 | 0 | 0 | 0 | |
| 3260 | 0 | 10 | 0 | 32600 | |
| 3270 | 0 | 0 | 0 | 0 | |
| 3280 | 0 | 1 | 0 | 3280 | |
| | | | | | |
| | | | | | |
| | | | 4527670 | 4607780 | -1.738581 |

Table B.2: Office System 2, before and after improvement

| Energy Consumption kwh | Bin size after Improvement | Bin size before Improvement | Total EC After | Total EC Before | Net Difference |
|---|---|---|---|---|---|
| 3720 | 0 | 0 | 0 | 0 | |
| 3730 | 0 | 0 | 0 | 0 | |
| 3740 | 0 | 0 | 0 | 0 | |
| 3750 | 0 | 0 | 0 | 0 | |
| 3760 | 0 | 0 | 0 | 0 | |
| 3770 | 1 | 0 | 3770 | 0 | |
| 3780 | 52 | 0 | 196560 | 0 | |
| 3790 | 47 | 5 | 178130 | 18950 | |
| 3800 | 94 | 17 | 357200 | 64600 | |
| 3810 | 146 | 47 | 556260 | 179070 | |
| 3820 | 120 | 85 | 458400 | 324700 | |
| 3830 | 46 | 130 | 176180 | 497900 | |
| 3840 | 32 | 95 | 122880 | 364800 | |
| 3850 | 53 | 78 | 204050 | 300300 | |
| 3860 | 78 | 37 | 301080 | 142820 | |
| 3870 | 132 | 9 | 510840 | 34830 | |
| 3880 | 89 | 17 | 345320 | 65960 | |
| 3890 | 66 | 34 | 256740 | 132260 | |
| 3900 | 25 | 67 | 97500 | 261300 | |
| 3910 | 33 | 76 | 129030 | 297160 | |
| 3920 | 29 | 107 | 113680 | 419440 | |
| 3930 | 75 | 80 | 294750 | 314400 | |
| 3940 | 72 | 72 | 283680 | 283680 | |
| 3950 | 81 | 28 | 319950 | 110600 | |
| 3960 | 126 | 16 | 498960 | 63360 | |
| 3970 | 54 | 4 | 214380 | 15880 | |
| 3980 | 37 | 21 | 147260 | 83580 | |
| 3990 | 11 | 24 | 43890 | 95760 | |
| 4000 | 1 | 61 | 4000 | 244000 | |
| 4010 | 0 | 55 | 0 | 220550 | |
| 4020 | 0 | 107 | 0 | 430140 | |
| 4030 | 0 | 59 | 0 | 237770 | |
| 4040 | 0 | 86 | 0 | 347440 | |

Table B.2 continued

| | | | | | |
|---|---|---|---|---|---|
| 4050 | 0 | 36 | 0 | 145800 | |
| 4060 | 0 | 29 | 0 | 117740 | |
| 4070 | 0 | 10 | 0 | 40700 | |
| 4080 | 0 | 8 | 0 | 32640 | |
| 4090 | 0 | 0 | 0 | 0 | |
| 4100 | 0 | 0 | 0 | 0 | |
| | | | | | |
| | | | | | |
| | | | 5814490 | 5888130 | -1.2506517 |

Table B.3: Office System 3, before and after improvement

| Energy Consumption kwh | Bin size after improvement | Bin size before improvement | Total EC after | Total EC before | Net Difference |
|---|---|---|---|---|---|
| 3050 | 0 | 5 | 0 | 15250 | |
| 3100 | 0 | 0 | 0 | 0 | |
| 3900 | 0 | 0 | 0 | 0 | |
| 4000 | 6 | 0 | 24000 | 0 | |
| 4010 | 92 | 25 | 368920 | 100250 | |
| 4020 | 42 | 58 | 168840 | 233160 | |
| 4030 | 120 | 126 | 483600 | 507780 | |
| 4040 | 131 | 137 | 529240 | 553480 | |
| 4050 | 134 | 80 | 542700 | 324000 | |
| 4060 | 94 | 63 | 381640 | 255780 | |
| 4070 | 140 | 11 | 569800 | 44770 | |
| 4080 | 73 | 0 | 297840 | 0 | |
| 4090 | 80 | 1 | 327200 | 4090 | |
| 4100 | 56 | 7 | 229600 | 28700 | |
| 4110 | 36 | 52 | 147960 | 213720 | |
| 4120 | 25 | 70 | 103000 | 288400 | |
| 4130 | 35 | 109 | 144550 | 450170 | |
| 4140 | 34 | 46 | 140760 | 190440 | |
| 4150 | 59 | 70 | 244850 | 290500 | |
| 4160 | 56 | 67 | 232960 | 278720 | |
| 4170 | 38 | 26 | 158460 | 108420 | |
| 4180 | 73 | 17 | 305140 | 71060 | |
| 4190 | 83 | 28 | 347770 | 117320 | |
| 4200 | 32 | 383 | 134400 | 1608600 | |
| 4210 | 40 | 1 | 168400 | 4210 | |
| 4220 | 20 | 0 | 84400 | 0 | |
| 4230 | 1 | 0 | 4230 | 0 | |
| 4240 | 0 | 0 | 0 | 0 | |
| 4250 | 0 | 0 | 0 | 0 | |
| 4260 | 0 | 0 | 0 | 0 | |
| 4270 | 0 | 0 | 0 | 0 | |
| 4280 | 0 | 0 | 0 | 0 | |

Table B.3 continued

| | | | | | |
|---|---|---|---|---|---|
| 4290 | 0 | 0 | 0 | 0 | |
| 4300 | 0 | 118 | 0 | 507400 | |
| | | | | | |
| | | | | | |
| | | | 6140260 | 6196220 | -0.903131 |

Table B.4: Office System 4, before and after improvement

| Energy Consumption kwh | Bin size after improvement | Bin size before improvement | Total EC after | Total EC before | Net Difference |
|---|---|---|---|---|---|
| 3720 | 13 | 9 | 48360 | 33480 | |
| 3730 | 87 | 42 | 324510 | 156660 | |
| 3740 | 42 | 86 | 157080 | 321640 | |
| 3750 | 35 | 32 | 131250 | 120000 | |
| 3760 | 22 | 2 | 82720 | 7520 | |
| 3770 | 118 | 45 | 444860 | 169650 | |
| 3780 | 195 | 105 | 737100 | 396900 | |
| 3790 | 166 | 75 | 629140 | 284250 | |
| 3800 | 65 | 95 | 247000 | 361000 | |
| 3810 | 11 | 8 | 41910 | 30480 | |
| 3820 | 82 | 1 | 313240 | 3820 | |
| 3830 | 70 | 0 | 268100 | 0 | |
| 3840 | 123 | 1 | 472320 | 3840 | |
| 3850 | 23 | 0 | 88550 | 0 | |
| 3860 | 25 | 0 | 96500 | 0 | |
| 3870 | 0 | 0 | 0 | 0 | |
| 3880 | 40 | 1 | 155200 | 3880 | |
| 3890 | 0 | 0 | 0 | 0 | |
| 3900 | 27 | 12 | 105300 | 46800 | |
| 3910 | 0 | 0 | 0 | 0 | |
| 3920 | 1 | 77 | 3920 | 301840 | |
| 3930 | 0 | 0 | 0 | 0 | |
| 3940 | 0 | 132 | 0 | 520080 | |
| 3950 | 0 | 0 | 0 | 0 | |
| 3960 | 8 | 121 | 31680 | 479160 | |
| 3970 | 0 | 0 | 0 | 0 | |
| 3980 | 51 | 163 | 202980 | 648740 | |
| 3990 | 0 | 0 | 0 | 0 | |
| 4000 | 93 | 119 | 372000 | 476000 | |
| 4010 | 0 | 0 | 0 | 0 | |
| 4020 | 82 | 195 | 329640 | 783900 | |
| 4030 | 0 | 0 | 0 | 0 | |
| 4040 | 90 | 59 | 363600 | 238360 | |

Table B.4 continued

| | | | | | |
|---|---|---|---|---|---|
| 4050 | 0 | 0 | 0 | 0 | |
| 4060 | 31 | 42 | 125860 | 170520 | |
| 4070 | 0 | 0 | 0 | 0 | |
| 4080 | 0 | 71 | 0 | 289680 | |
| 4090 | 0 | 0 | 0 | 0 | |
| 4100 | 0 | 7 | 0 | 28700 | |
| | | | | | |
| | | | | | |
| | | | 5772820 | 5876900 | -1.7710017 |

Table B.5: Office System 5, before and after improvement

| Energy Consumption kwh | Bin size after improvement | Bin size before improvement | Total EC after | Total EC before | Net Difference |
|---|---|---|---|---|---|
| 2280 | 0 | 0 | 0 | 0 | |
| 2300 | 18 | 0 | 41400 | 0 | |
| 2320 | 95 | 115 | 220400 | 266800 | |
| 2340 | 25 | 2 | 58500 | 4680 | |
| 2360 | 224 | 207 | 528640 | 488520 | |
| 2380 | 132 | 110 | 314160 | 261800 | |
| 2400 | 115 | 115 | 276000 | 276000 | |
| 2420 | 104 | 97 | 251680 | 234740 | |
| 2440 | 157 | 142 | 383080 | 346480 | |
| 2460 | 24 | 109 | 59040 | 268140 | |
| 2480 | 98 | 21 | 243040 | 52080 | |
| 2500 | 69 | 109 | 172500 | 272500 | |
| 2520 | 63 | 101 | 158760 | 254520 | |
| 2540 | 7 | 20 | 17780 | 50800 | |
| 2560 | 181 | 53 | 463360 | 135680 | |
| 2580 | 64 | 162 | 165120 | 417960 | |
| 2600 | 38 | 27 | 98800 | 70200 | |
| 2620 | 81 | 19 | 212220 | 49780 | |
| 2640 | 5 | 89 | 13200 | 234960 | |
| 2660 | 0 | 2 | 0 | 5320 | |
| | | | | | |
| | | | | | |
| | | | 3677680 | 3690960 | -0.359798 |

Table B.6: Office System 6, before and after improvement

| Energy Consumption kwh | Bin size after improvement | Bin size before improvement | Total EC after | Total EC before | Net Difference |
|---|---|---|---|---|---|
| 3150 | 1 | 0 | 3150 | 0 | |
| 3160 | 130 | 1 | 410800 | 3160 | |
| 3170 | 47 | 1 | 148990 | 3170 | |
| 3180 | 262 | 118 | 833160 | 375240 | |
| 3190 | 102 | 35 | 325380 | 111650 | |
| 3200 | 165 | 28 | 528000 | 89600 | |
| 3210 | 59 | 260 | 189390 | 834600 | |
| 3220 | 50 | 46 | 161000 | 148120 | |
| 3230 | 165 | 27 | 532950 | 87210 | |
| 3240 | 53 | 15 | 171720 | 48600 | |
| 3250 | 64 | 141 | 208000 | 458250 | |
| 3260 | 110 | 95 | 358600 | 309700 | |
| 3270 | 127 | 61 | 415290 | 199470 | |
| 3280 | 71 | 108 | 232880 | 354240 | |
| 3290 | 72 | 38 | 236880 | 125020 | |
| 3300 | 22 | 41 | 72600 | 135300 | |
| 3310 | 0 | 34 | 0 | 112540 | |
| 3320 | 0 | 59 | 0 | 195880 | |
| 3330 | 0 | 75 | 0 | 249750 | |
| 3340 | 0 | 105 | 0 | 350700 | |
| 3350 | 0 | 87 | 0 | 291450 | |
| 3360 | 0 | 54 | 0 | 181440 | |
| 3370 | 0 | 32 | 0 | 107840 | |
| 3380 | 0 | 21 | 0 | 70980 | |
| 3390 | 0 | 15 | 0 | 50850 | |
| 3400 | 0 | 3 | 0 | 10200 | |
| 3410 | 0 | 0 | 0 | 0 | |
| | | | | | |
| | | | | | |
| | | | 4828790 | 4904960 | -1.5529179 |

Table B.7: Office first year average system energy consumption comparison

| System 1 | bin | System 2 | bin | System 3 | bin | System 4 | bin | System 5 | bin | System 6 | bin | Average |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2900 | 0.00 | 3790 | 5.00 | 3050 | 4.00 | 3720 | 9 | 2280 | 2.00 | 3160 | 1 | 72350 |
| 2920 | 0.00 | 3800 | 17.00 | 3100 | 3.00 | 3730 | 42 | 2300 | 115.00 | 3170 | 1 | 498230 |
| 2940 | 124.00 | 3810 | 47.00 | 3900 | 0.00 | 3740 | 86 | 2320 | 1.00 | 3180 | 118 | 1242830 |
| 2960 | 132.00 | 3820 | 85.00 | 4000 | 7.00 | 3750 | 32 | 2340 | 314.00 | 3190 | 35 | 1709830 |
| 2980 | 147.00 | 3830 | 130.00 | 4010 | 20.00 | 3760 | 2 | 2360 | 92.00 | 3200 | 28 | 1330400 |
| 3000 | 108.00 | 3840 | 95.00 | 4020 | 47.00 | 3770 | 45 | 2380 | 243.00 | 3210 | 260 | 2460330 |
| 3020 | 121.00 | 3850 | 78.00 | 4030 | 80.00 | 3780 | 105 | 2400 | 133.00 | 3220 | 46 | 1852340 |
| 3040 | 81.00 | 3860 | 37.00 | 4040 | 129.00 | 3790 | 75 | 2420 | 89.00 | 3230 | 27 | 1497060 |
| 3060 | 97.00 | 3870 | 9.00 | 4050 | 118.00 | 3800 | 95 | 2440 | 45.00 | 3240 | 15 | 1328950 |
| 3080 | 49.00 | 3880 | 17.00 | 4060 | 79.00 | 3810 | 8 | 2460 | 38.00 | 3250 | 141 | 1119830 |
| 3100 | 51.00 | 3890 | 34.00 | 4070 | 20.00 | 3820 | 1 | 2480 | 89.00 | 3260 | 95 | 906000 |
| 3120 | 123.00 | 3900 | 67.00 | 4080 | 0.00 | 3830 | 0 | 2500 | 43.00 | 3270 | 61 | 952030 |
| 3140 | 77.00 | 3910 | 76.00 | 4090 | 4.00 | 3840 | 1 | 2520 | 165.00 | 3280 | 108 | 1329180 |
| 3160 | 84.00 | 3920 | 107.00 | 4100 | 2.00 | 3850 | 0 | 2540 | 33.00 | 3290 | 38 | 901920 |
| 3180 | 103.00 | 3930 | 80.00 | 4110 | 43.00 | 3860 | 0 | 2560 | 92.00 | 3300 | 41 | 1189490 |
| 3200 | 70.00 | 3940 | 72.00 | 4120 | 78.00 | 3870 | 0 | 2580 | 6.00 | 3310 | 34 | 957060 |
| 3220 | 37.00 | 3950 | 28.00 | 4130 | 118.00 | 3880 | 1 | | | 3320 | 59 | 916840 |
| 3240 | 85.00 | 3960 | 16.00 | 4140 | 44.00 | 3890 | 0 | | | 3330 | 75 | 770670 |
| 3260 | 10.00 | 3970 | 4.00 | 4150 | 77.00 | 3900 | 12 | | | 3340 | 105 | 765530 |
| 3280 | 1.00 | 3980 | 21.00 | 4160 | 69.00 | 3910 | 0 | | | 3350 | 87 | 665350 |
| | | 3990 | 24.00 | 4170 | 30.00 | 3920 | 77 | | | 3360 | 54 | 704140 |
| | | 4000 | 61.00 | 4180 | 22.00 | 3930 | 0 | | | 3370 | 32 | 443800 |
| | | 4010 | 55.00 | 4190 | 7.00 | 3940 | 132 | | | 3380 | 21 | 840940 |
| | | 4020 | 107.00 | 4200 | 6.00 | 3950 | 0 | | | 3390 | 15 | 506190 |
| | | 4030 | 59.00 | 4210 | 4.00 | 3960 | 121 | | | 3400 | 3 | 743970 |
| | | 4040 | 86.00 | 4250 | 390.00 | 3970 | 0 | | | | | 2004940 |
| | | 4050 | 36.00 | 4300 | 99.00 | 3980 | 163 | | | | | 1220240 |
| | | 4060 | 29.00 | | | 3990 | 0 | | | | | 117740 |
| | | 4070 | 10.00 | | | 4000 | 119 | | | | | 516700 |
| | | 4080 | 8.00 | | | 4010 | 0 | | | | | 32640 |
| | | | | | | 4020 | 195 | | | | | 783900 |
| | | | | | | 4030 | 0 | | | | | 0 |
| | | | | | | 4040 | 59 | | | | | 238360 |
| | | | | | | 4050 | 0 | | | | | 0 |
| | | | | | | 4060 | 42 | | | | | 170520 |
| | | | | | | 4070 | 0 | | | | | 0 |
| | | | | | | 4080 | 71 | | | | | 289680 |
| | | | | | | 4090 | 0 | | | | | 0 |
| | | | | | | 4100 | 7 | | | | | 28700 |
| | | | | | | | | | | | | |
| | | | | | | | | | | | | 3456.52 |

Table B.8: Healthcare first year average; system energy consumption comparison

| System 1 | bin | System 2 | bin | System 3 | bin | System 4 | bin | System 5 | bin | System 6 | bin | Average |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2980 | 1.00 | 3930 | 32.00 | 3100 | 10.00 | 3860 | 9.00 | 2470 | 2.00 | 3410 | 1.00 | 202830 |
| 2990 | 12.00 | 3940 | 23.00 | 4160 | 3.00 | 3870 | 65.00 | 2480 | 102.00 | 3420 | 118.00 | 1047050 |
| 3000 | 38.00 | 3950 | 30.00 | 4170 | 24.00 | 3880 | 16.00 | 2490 | 17.00 | 3430 | 12.00 | 478150 |
| 3010 | 4.00 | 3960 | 128.00 | 4180 | 36.00 | 3890 | 37.00 | 2500 | 0.00 | 3440 | 252.00 | 1680210 |
| 3020 | 48.00 | 3970 | 80.00 | 4190 | 155.00 | 3900 | 39.00 | 2510 | 0.00 | 3450 | 47.00 | 1426260 |
| 3030 | 2.00 | 3980 | 115.00 | 4200 | 70.00 | 3910 | 11.00 | 2520 | 46.00 | 3460 | 51.00 | 1093150 |
| 3040 | 83.00 | 3990 | 65.00 | 4210 | 85.00 | 3920 | 41.00 | 2530 | 221.00 | 3470 | 21.00 | 1662240 |
| 3050 | 60.00 | 4000 | 18.00 | 4220 | 98.00 | 3930 | 88.00 | 2540 | 137.00 | 3480 | 7.00 | 1386740 |
| 3060 | 79.00 | 4010 | 17.00 | 4230 | 26.00 | 3940 | 43.00 | 2550 | 0.00 | 3490 | 25.00 | 676560 |
| 3070 | 103.00 | 4020 | 20.00 | 4240 | 3.00 | 3950 | 135.00 | 2560 | 40.00 | 3500 | 101.00 | 1398480 |
| 3080 | 26.00 | 4030 | 33.00 | 4250 | 2.00 | 3960 | 18.00 | 2570 | 40.00 | 3510 | 98.00 | 739630 |
| 3090 | 31.00 | 4040 | 64.00 | 4260 | 2.00 | 3970 | 0.00 | 2580 | 227.00 | 3520 | 70.00 | 1194930 |
| 3100 | 71.00 | 4050 | 69.00 | 4270 | 36.00 | 3980 | 0.00 | 2590 | 12.00 | 3530 | 117.00 | 1097360 |
| 3110 | 4.00 | 4060 | 90.00 | 4280 | 37.00 | 3990 | 0.00 | 2600 | 33.00 | 3540 | 48.00 | 791920 |
| 3120 | 127.00 | 4070 | 86.00 | 4290 | 60.00 | 4000 | 0.00 | 2610 | 0.00 | 3550 | 35.00 | 1127910 |
| 3130 | 8.00 | 4080 | 43.00 | 4300 | 62.00 | 4010 | 0.00 | 2620 | 75.00 | 3560 | 43.00 | 816660 |
| 3140 | 110.00 | 4090 | 57.00 | 4310 | 93.00 | 4020 | 1.00 | 2630 | 0.00 | 3570 | 57.00 | 1186870 |
| 3150 | 0.00 | 4100 | 20.00 | 4320 | 80.00 | 4030 | 0.00 | 2640 | 59.00 | 3580 | 16.00 | 640640 |
| 3160 | 54.00 | 4110 | 15.00 | 4330 | 42.00 | 4040 | 19.00 | 2650 | 0.00 | 3590 | 111.00 | 889400 |
| 3170 | 0.00 | 4120 | 16.00 | 4340 | 42.00 | 4050 | 0.00 | 2660 | 38.00 | 3600 | 106.00 | 730880 |
| 3180 | 33.00 | 4130 | 18.00 | 4350 | 18.00 | 4060 | 42.00 | 2670 | 0.00 | 3610 | 48.00 | 601380 |
| 3190 | 0.00 | 4140 | 68.00 | 4360 | 16.00 | 4070 | 0.00 | 2680 | 102.00 | 3620 | 59.00 | 838220 |
| 3200 | 93.00 | 4150 | 45.00 | 4370 | 15.00 | 4080 | 77.00 | 2690 | 0.00 | 3630 | 42.00 | 1016520 |
| 3210 | 0.00 | 4160 | 99.00 | 4380 | 3.00 | 4090 | 0.00 | 2700 | 19.00 | 3640 | 3.00 | 487200 |
| 3220 | 84.00 | 4170 | 45.00 | 4390 | 2.00 | 4100 | 92.00 | 2710 | 0.00 | 3650 | 12.00 | 887910 |
| 3230 | 0.00 | 4180 | 89.00 | 4400 | 380.00 | 4110 | 0.00 | 2720 | 121.00 | | | 2373140 |
| 3240 | 56.00 | 4190 | 40.00 | 4410 | 0.00 | 4120 | 197.00 | 2730 | 0.00 | | | 1160680 |
| 3250 | 0.00 | 4200 | 47.00 | 4420 | 0.00 | 4130 | 0.00 | 2740 | 85.00 | | | 430300 |
| 3260 | 114.00 | 4210 | 22.00 | 4430 | 0.00 | 4140 | 70.00 | 2750 | 0.00 | | | 754060 |
| 3270 | 0.00 | 4220 | 4.00 | 4440 | 0.00 | 4150 | 0.00 | 2760 | 88.00 | | | 259760 |
| 3280 | 79.00 | 4230 | 2.00 | 4450 | 0.00 | 4160 | 138.00 | 2770 | 0.00 | | | 841660 |
| 3290 | 0.00 | | | 4460 | 0.00 | 4170 | 0.00 | 2780 | 36.00 | | | 100080 |
| 3300 | 68.00 | | | 4470 | 0.00 | 4180 | 185.00 | | | | | 997700 |
| 3310 | 0.00 | | | 4480 | 0.00 | 4190 | 0.00 | | | | | 0 |
| 3320 | 32.00 | | | 4490 | 0.00 | 4200 | 73.00 | | | | | 412840 |
| 3330 | 0.00 | | | 4500 | 100.00 | 4210 | 0.00 | | | | | 450000 |
| 3340 | 57.00 | | | | | 4220 | 56.00 | | | | | 426700 |
| 3350 | 0.00 | | | | | 4230 | 0.00 | | | | | 0 |
| 3360 | 23.00 | | | | | 4240 | 46.00 | | | | | 272320 |
| | | | | | | 4250 | 0.00 | | | | | 0 |
| | | | | | | 4260 | 2.00 | | | | | 8520 |
| | | | | | | | | | | | | |
| | | | | | | | | | | | | 3620.76 |

Table B.9: Healthcare 5 years average; system energy consumption comparison

| System 1 | bin | System 2 | bin | System 3 | bin | System 4 | bin | System 5 | bin | System 6 | bin | Average |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 3010 | 1.00 | 3960 | 2.00 | 3200 | 5.00 | 3890 | 2.00 | 2490 | 1.00 | 3450 | 25.00 | 123450 |
| 3020 | 12.00 | 3970 | 29.00 | 4200 | 3.00 | 3900 | 18.00 | 2500 | 104.00 | 3460 | 104.00 | 854010 |
| 3030 | 37.00 | 3980 | 42.00 | 4210 | 18.00 | 3910 | 52.00 | 2510 | 17.00 | 3470 | 30.00 | 705140 |
| 3040 | 8.00 | 3990 | 37.00 | 4220 | 30.00 | 3920 | 22.00 | 2520 | 0.00 | 3480 | 235.00 | 1202590 |
| 3050 | 44.00 | 4000 | 112.00 | 4230 | 58.00 | 3930 | 50.00 | 2530 | 0.00 | 3490 | 43.00 | 1174110 |
| 3060 | 2.00 | 4010 | 95.00 | 4240 | 175.00 | 3940 | 20.00 | 2540 | 1.00 | 3500 | 50.00 | 1385410 |
| 3070 | 84.00 | 4020 | 126.00 | 4250 | 68.00 | 3950 | 21.00 | 2550 | 161.00 | 3510 | 13.00 | 1592530 |
| 3080 | 58.00 | 4030 | 30.00 | 4260 | 62.00 | 3960 | 95.00 | 2560 | 122.00 | 3520 | 0.00 | 1252180 |
| 3090 | 31.00 | 4040 | 16.00 | 4270 | 76.00 | 3970 | 50.00 | 2570 | 0.00 | 3530 | 0.00 | 683450 |
| 3100 | 107.00 | 4050 | 11.00 | 4280 | 10.00 | 3980 | 105.00 | 2580 | 110.00 | 3540 | 5.00 | 1138450 |
| 3110 | 7.00 | 4060 | 0.00 | 4290 | 0.00 | 3990 | 62.00 | 2590 | 16.00 | 3550 | 14.00 | 360290 |
| 3120 | 66.00 | 4070 | 0.00 | 4300 | 0.00 | 4000 | 4.00 | 2600 | 42.00 | 3560 | 33.00 | 448600 |
| 3130 | 15.00 | 4080 | 0.00 | 4310 | 0.00 | 4010 | 0.00 | 2610 | 46.00 | 3570 | 37.00 | 299100 |
| 3140 | 32.00 | 4090 | 14.00 | 4320 | 0.00 | 4020 | 1.00 | 2620 | 29.00 | 3580 | 102.00 | 602900 |
| 3150 | 49.00 | 4100 | 18.00 | 4330 | 1.00 | 4030 | 0.00 | 2630 | 0.00 | 3590 | 76.00 | 505320 |
| 3160 | 60.00 | 4110 | 45.00 | 4340 | 1.00 | 4040 | 0.00 | 2640 | 156.00 | 3600 | 134.00 | 1273130 |
| 3170 | 0.00 | 4120 | 35.00 | 4350 | 4.00 | 4050 | 0.00 | 2650 | 0.00 | 3610 | 53.00 | 352930 |
| 3180 | 74.00 | 4130 | 77.00 | 4360 | 40.00 | 4060 | 0.00 | 2660 | 50.00 | 3620 | 35.00 | 987430 |
| 3190 | 0.00 | 4140 | 85.00 | 4370 | 69.00 | 4070 | 0.00 | 2670 | 0.00 | 3630 | 9.00 | 686100 |
| 3200 | 40.00 | 4150 | 80.00 | 4380 | 49.00 | 4080 | 0.00 | 2680 | 35.00 | 3640 | 2.00 | 775700 |
| 3210 | 0 | 4160 | 62 | 4390 | 46 | 4090 | 0 | 2690 | 0 | 3650 | 14 | 510960 |
| 3220 | 76 | 4170 | 49 | 4400 | 104 | 4100 | 1 | 2700 | 115 | 3660 | 13 | 1268830 |
| 3230 | 0 | 4180 | 26 | 4410 | 74 | 4110 | 0 | 2710 | 0 | 3670 | 42 | 589160 |
| 3240 | 41 | 4190 | 8 | 4420 | 33 | 4120 | 0 | 2720 | 62 | 3680 | 28 | 583900 |
| 3250 | 0 | 4200 | 1 | 4430 | 19 | 4130 | 0 | 2730 | 0 | 3690 | 79 | 379880 |
| 3260 | 80 | 4210 | 0 | 4440 | 28 | 4140 | 2 | 2740 | 78 | 3700 | 46 | 777320 |
| 3270 | 0 | 4220 | 0 | 4450 | 9 | 4150 | 0 | 2750 | 0 | 3710 | 113 | 459280 |
| 3280 | 84 | 4230 | 4 | 4460 | 17 | 4160 | 33 | 2760 | 23 | 3720 | 46 | 740140 |
| 3290 | 0 | 4240 | 10 | 4470 | 4 | 4170 | 0 | 2770 | 0 | 3730 | 66 | 306460 |
| 3300 | 119 | 4250 | 11 | 4480 | 2 | 4180 | 105 | 2780 | 80 | 3740 | 27 | 1210690 |
| 3310 | 0 | 4260 | 25 | 4490 | 0 | 4190 | 0 | 2790 | 0 | 3750 | 16 | 166500 |
| 3320 | 52 | 4270 | 80 | 4500 | 45 | 4200 | 175 | 2800 | 112 | 3760 | 10 | 1802940 |
| 3330 | 0 | 4280 | 59 | 4510 | 0 | 4210 | 0 | 2810 | 0 | | | 252520 |
| 3340 | 64 | 4290 | 51 | 4520 | 0 | 4220 | 76 | 2820 | 31 | | | 840690 |
| 3350 | 0 | 4300 | 117 | 4530 | 0 | 4230 | 0 | 2830 | 0 | | | 503100 |
| 3360 | 23 | 4310 | 44 | 4540 | 0 | 4240 | 130 | 2840 | 53 | | | 968640 |
| 3370 | 0 | 4320 | 31 | 4550 | 0 | 4250 | 0 | 2850 | 0 | | | 133920 |
| 3380 | 79 | 4330 | 51 | 4560 | 0 | 4260 | 167 | 2860 | 54 | | | 1353710 |
| 3390 | 0 | 4340 | 8 | 4570 | 0 | 4270 | 0 | 2870 | 0 | | | 34720 |
| 3400 | 31 | 4350 | 7 | 4580 | 0 | 4280 | 44 | 2880 | 2 | | | 329930 |
| 3410 | 0 | 4360 | 1 | 4590 | 0 | 4290 | 0 | | | | | 4360 |
| 3420 | 59 | 4370 | 1 | 4600 | 450 | 4300 | 60 | | | | | 2534150 |
| 3430 | 0 | | | | | 4310 | 0 | | | | | 0 |
| 3440 | 33 | | | | | 4320 | 62 | | | | | 381360 |
| 3450 | 0 | | | | | 4330 | 0 | | | | | 0 |
| 3460 | 30 | | | | | 4340 | 30 | | | | | 234000 |
| 3470 | 0 | | | | | 4350 | 0 | | | | | 0 |
| 3480 | 2 | | | | | 4360 | 68 | | | | | 303440 |
| | | | | | | 4370 | 0 | | | | | 0 |
| | | | | | | 4380 | 41.00 | | | | | 179580 |
| | | | | | | 4390 | 0.00 | | | | | 0 |
| | | | | | | 4400 | 4.00 | | | | | 17600 |
| | | | | | | | | | | | | |
| | | | | | | | | | | | | 3696.73 |

Table B.10: Healthcare 1 years; system energy consumption comparison

| System | bin | System | bin | System | bin | System | bin | System | bin | System | bin | - |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 3100 | 2 | 4090 | 0 | 3100 | 10 | 4040 | 19 | 2560 | 30 | 3540 | 4 | 204920 |
| 3120 | 8 | 4100 | 1 | 4300 | 10 | 4060 | 38 | 2580 | 91 | 3550 | 5 | 478870 |
| 3140 | 70 | 4110 | 4 | 4400 | 380 | 4080 | 44 | 2600 | 17 | 3560 | 37 | 2263680 |
| 3160 | 51 | 4120 | 16 | 4500 | 100 | 4100 | 17 | 2620 | 62 | 3570 | 57 | 1112710 |
| 3180 | 26 | 4130 | 18 | | | 4120 | 66 | 2640 | 59 | 3580 | 16 | 641980 |
| 3200 | 69 | 4140 | 68 | | | 4140 | 35 | 2680 | 3 | 3590 | 111 | 1053750 |
| 3220 | 16 | 4150 | 45 | | | 4160 | 52 | 2700 | 15 | 3600 | 106 | 876690 |
| 3240 | 1 | 4160 | 99 | | | 4180 | 65 | 2720 | 81 | 3610 | 48 | 1080380 |
| 3260 | 46 | 4170 | 45 | | | 4200 | 60 | 2740 | 18 | 3620 | 59 | 852510 |
| 3280 | 39 | 4180 | 89 | | | 4220 | 56 | 2760 | 88 | 3630 | 42 | 1131600 |
| 3300 | 60 | 4190 | 40 | | | 4240 | 46 | 2780 | 36 | 3640 | 3 | 671640 |
| 3320 | 32 | 4200 | 47 | | | 4260 | 2 | | | 3650 | 12 | 355960 |
| 3340 | 57 | 4210 | 22 | | | | | | | | | 283000 |
| 3360 | 23 | 4220 | 4 | | | | | | | | | 94160 |
| | | 4230 | 2 | | | | | | | | | 8460 |
| | | | | | | | | | | | | 3703.43667 |

Table B.11: Healthcare System 1, before and after improvement

| Energy Consumption kwh | Bin size after improvement | Bin size before improvement | Total EC after | Total EC before | Net Difference |
|---|---|---|---|---|---|
| 2980 | 6 | 1 | 17880 | 2980 | |
| 2990 | 17 | 12 | 50830 | 35880 | |
| 3000 | 38 | 38 | 114000 | 114000 | |
| 3010 | 8 | 4 | 24080 | 12040 | |
| 3020 | 43 | 48 | 129860 | 144960 | |
| 3030 | 4 | 2 | 12120 | 6060 | |
| 3040 | 27 | 83 | 82080 | 252320 | |
| 3050 | 117 | 60 | 356850 | 183000 | |
| 3060 | 65 | 79 | 198900 | 241740 | |
| 3070 | 135 | 103 | 414450 | 316210 | |
| 3080 | 36 | 26 | 110880 | 80080 | |
| 3090 | 24 | 31 | 74160 | 95790 | |
| 3100 | 48 | 71 | 148800 | 220100 | |
| 3110 | 32 | 4 | 99520 | 12440 | |
| 3120 | 93 | 127 | 290160 | 396240 | |
| 3130 | 65 | 8 | 203450 | 25040 | |
| 3140 | 67 | 110 | 210380 | 345400 | |
| 3150 | 0 | 0 | 0 | 0 | |
| 3160 | 37 | 54 | 116920 | 170640 | |
| 3170 | 27 | 0 | 85590 | 0 | |
| 3180 | 29 | 33 | 92220 | 104940 | |
| 3190 | 55 | 0 | 175450 | 0 | |
| 3200 | 67 | 93 | 214400 | 297600 | |
| 3210 | 0 | 0 | 0 | 0 | |
| 3220 | 34 | 84 | 109480 | 270480 | |
| 3230 | 30 | 0 | 96900 | 0 | |
| 3240 | 28 | 56 | 90720 | 181440 | |
| 3250 | 37 | 0 | 120250 | 0 | |
| 3260 | 45 | 114 | 146700 | 371640 | |
| 3270 | 22 | 0 | 71940 | 0 | |
| 3280 | 68 | 79 | 223040 | 259120 | |
| 3290 | 58 | 0 | 190820 | 0 | |

Table B.11 continued

| | | | | | |
|---|---|---|---|---|---|
| 3300 | 24 | 68 | 79200 | 224400 | |
| 3310 | 0 | 0 | 0 | 0 | |
| 3320 | 28 | 32 | 92960 | 106240 | |
| 3330 | 32 | 0 | 106560 | 0 | |
| 3340 | 34 | 57 | 113560 | 190380 | |
| 3350 | 14 | 0 | 46900 | 0 | |
| 3360 | 6 | 23 | 20160 | 77280 | |
| | | | | | |
| | | | | | |
| | | | 4732170 | 4738440 | -0.132322 |

Table B.12: Healthcare System 2, before and after improvement

| Energy Consumption kwh | Bin size after improvement | Bin size before improvement | Total EC after | Total EC before | Net Difference |
|---|---|---|---|---|---|
| 3910 | 1 | 0 | 3910 | 0 | |
| 3920 | 2 | 0 | 7840 | 0 | |
| 3930 | 59 | 32 | 231870 | 125760 | |
| 3940 | 10 | 23 | 39400 | 90620 | |
| 3950 | 173 | 30 | 683350 | 118500 | |
| 3960 | 50 | 128 | 198000 | 506880 | |
| 3970 | 146 | 80 | 579620 | 317600 | |
| 3980 | 35 | 115 | 139300 | 457700 | |
| 3990 | 14 | 65 | 55860 | 259350 | |
| 4000 | 22 | 18 | 88000 | 72000 | |
| 4010 | 18 | 17 | 72180 | 68170 | |
| 4020 | 50 | 20 | 201000 | 80400 | |
| 4030 | 35 | 33 | 141050 | 132990 | |
| 4040 | 78 | 64 | 315120 | 258560 | |
| 4050 | 65 | 69 | 263250 | 279450 | |
| 4060 | 75 | 90 | 304500 | 365400 | |
| 4070 | 73 | 86 | 297110 | 350020 | |
| 4080 | 53 | 43 | 216240 | 175440 | |
| 4090 | 38 | 57 | 155420 | 233130 | |
| 4100 | 30 | 20 | 123000 | 82000 | |
| 4110 | 51 | 15 | 209610 | 61650 | |
| 4120 | 29 | 16 | 119480 | 65920 | |
| 4130 | 42 | 18 | 173460 | 74340 | |
| 4140 | 86 | 68 | 356040 | 281520 | |
| 4150 | 60 | 45 | 249000 | 186750 | |
| 4160 | 97 | 99 | 403520 | 411840 | |
| 4170 | 38 | 45 | 158460 | 187650 | |
| 4180 | 47 | 89 | 196460 | 372020 | |
| 4190 | 13 | 40 | 54470 | 167600 | |
| 4200 | 7 | 47 | 29400 | 197400 | |
| 4210 | 2 | 22 | 8420 | 92620 | |
| 4220 | 1 | 4 | 4220 | 16880 | |
| 4230 | 0 | 2 | 0 | 8460 | |
| | | | | | |
| | | | | | |
| | | | 6078560 | 6098620 | -0.3289268 |

Table B.13: Healthcare System 3, before and after improvement

| Energy Consumption kwh | Bin size after improvement | Bin size before improvement | Total EC after | Total EC before | Net Difference |
|---|---|---|---|---|---|
| 3100 | 0 | 10 | 0 | 31000 | |
| 4150 | 1 | 3 | 4150 | 12450 | |
| 4160 | 4 | 24 | 16640 | 99840 | |
| 4170 | 77 | 36 | 321090 | 150120 | |
| 4180 | 28 | 155 | 117040 | 647900 | |
| 4190 | 89 | 70 | 372910 | 293300 | |
| 4200 | 163 | 85 | 684600 | 357000 | |
| 4210 | 74 | 98 | 311540 | 412580 | |
| 4220 | 161 | 26 | 679420 | 109720 | |
| 4230 | 65 | 3 | 274950 | 12690 | |
| 4240 | 89 | 2 | 377360 | 8480 | |
| 4250 | 93 | 2 | 395250 | 8500 | |
| 4260 | 77 | 36 | 328020 | 153360 | |
| 4270 | 61 | 37 | 260470 | 157990 | |
| 4280 | 34 | 60 | 145520 | 256800 | |
| 4290 | 25 | 62 | 107250 | 265980 | |
| 4300 | 37 | 93 | 159100 | 399900 | |
| 4310 | 44 | 80 | 189640 | 344800 | |
| 4320 | 27 | 42 | 116640 | 181440 | |
| 4330 | 60 | 42 | 259800 | 181860 | |
| 4340 | 57 | 18 | 247380 | 78120 | |
| 4350 | 36 | 16 | 156600 | 69600 | |
| 4360 | 83 | 15 | 361880 | 65400 | |
| 4370 | 31 | 3 | 135470 | 13110 | |
| 4380 | 54 | 2 | 236520 | 8760 | |
| 4390 | 29 | 380 | 127310 | 1668200 | |
| 4400 | 1 | 0 | 4400 | 0 | |
| 4410 | 0 | 0 | 0 | 0 | |
| 4420 | 0 | 0 | 0 | 0 | |
| 4430 | 0 | 0 | 0 | 0 | |
| 4440 | 0 | 0 | 0 | 0 | |
| 4450 | 0 | 0 | 0 | 0 | |
| 4460 | 0 | 0 | 0 | 0 | |
| 4470 | 0 | 0 | 0 | 0 | |

Table B.13 continued

| | | | | | |
|---|---|---|---|---|---|
| 4480 | 0 | 0 | 0 | 0 | |
| 4490 | 0 | 100 | 0 | 449000 | |
| 4500 | 0 | 0 | 0 | 0 | |
| 4510 | 0 | 0 | 0 | 0 | |
| 4520 | 0 | 0 | 0 | 0 | |
| | | | | | |
| | | | | | |
| | | | 6390950 | 6437900 | -0.72927 |

Table B.14: Healthcare System 4, before and after improvement

| Energy Consumption kwh | Bin size after improvement | Bin size before improvement | Total EC after | Total EC before | Net Difference |
|---|---|---|---|---|---|
| 3860 | 17 | 9 | 65620 | 34740 | |
| 3870 | 60 | 65 | 232200 | 251550 | |
| 3880 | 18 | 16 | 69840 | 62080 | |
| 3890 | 61 | 37 | 237290 | 143930 | |
| 3900 | 70 | 39 | 273000 | 152100 | |
| 3910 | 62 | 11 | 242420 | 43010 | |
| 3920 | 182 | 41 | 713440 | 160720 | |
| 3930 | 71 | 88 | 279030 | 345840 | |
| 3940 | 144 | 43 | 567360 | 169420 | |
| 3950 | 96 | 135 | 379200 | 533250 | |
| 3960 | 69 | 18 | 273240 | 71280 | |
| 3970 | 67 | 0 | 265990 | 0 | |
| 3980 | 39 | 0 | 155220 | 0 | |
| 3990 | 62 | 0 | 247380 | 0 | |
| 4000 | 79 | 0 | 316000 | 0 | |
| 4010 | 26 | 0 | 104260 | 0 | |
| 4020 | 36 | 1 | 144720 | 4020 | |
| 4030 | 0 | 0 | 0 | 0 | |
| 4040 | 27 | 19 | 109080 | 76760 | |
| 4050 | 24 | 0 | 97200 | 0 | |
| 4060 | 0 | 42 | 0 | 170520 | |
| 4070 | 0 | 0 | 0 | 0 | |
| 4080 | 0 | 77 | 0 | 314160 | |
| 4090 | 0 | 0 | 0 | 0 | |
| 4100 | 0 | 92 | 0 | 377200 | |
| 4110 | 0 | 0 | 0 | 0 | |
| 4120 | 7 | 197 | 28840 | 811640 | |
| 4130 | 0 | 0 | 0 | 0 | |
| 4140 | 38 | 70 | 157320 | 289800 | |
| 4150 | 38 | 0 | 157700 | 0 | |
| 4160 | 38 | 138 | 158080 | 574080 | |
| 4170 | 0 | 0 | 0 | 0 | |
| 4180 | 38 | 185 | 158840 | 773300 | |
| 4190 | 56 | 0 | 234640 | 0 | |

Table B.14 continued

| | | | | | |
|---|---|---|---|---|---|
| 4200 | 51 | 73 | 214200 | 306600 | |
| 4210 | 0 | 0 | 0 | 0 | |
| 4220 | 29 | 56 | 122380 | 236320 | |
| 4230 | 10 | 0 | 42300 | 0 | |
| 4240 | 2 | 46 | 8480 | 195040 | |
| | | | | | |
| | | | | | |
| | | | 6055270 | 6097360 | -0.690298 |

Table B.15: Healthcare System 5, before and after improvement

| Energy Consumption kwh | Bin size after improvement | Bin size before improvement | Total EC after | Total EC before | Net Differen ce |
|---|---|---|---|---|---|
| 2470 | 10 | 2 | 24700 | 4940 | |
| 2480 | 20 | 102 | 49600 | 252960 | |
| 2490 | 15 | 17 | 37350 | 42330 | |
| 2500 | 16 | 0 | 40000 | 0 | |
| 2510 | 240 | 0 | 602400 | 0 | |
| 2520 | 36 | 46 | 90720 | 115920 | |
| 2530 | 73 | 221 | 184690 | 559130 | |
| 2540 | 67 | 137 | 170180 | 347980 | |
| 2550 | 79 | 0 | 201450 | 0 | |
| 2560 | 186 | 40 | 476160 | 102400 | |
| 2570 | 277 | 40 | 711890 | 102800 | |
| 2580 | 135 | 227 | 348300 | 585660 | |
| 2590 | 7 | 12 | 18130 | 31080 | |
| 2600 | 145 | 33 | 377000 | 85800 | |
| 2610 | 72 | 0 | 187920 | 0 | |
| 2620 | 14 | 75 | 36680 | 196500 | |
| 2630 | 47 | 0 | 123610 | 0 | |
| 2640 | 46 | 59 | 121440 | 155760 | |
| 2650 | 0 | 0 | 0 | 0 | |
| 2660 | 16 | 38 | 42560 | 101080 | |
| 2670 | 1 | 0 | 2670 | 0 | |
| 2680 | 0 | 102 | 0 | 273360 | |
| 2690 | 0 | 0 | 0 | 0 | |
| 2700 | 3 | 19 | 8100 | 51300 | |
| 2710 | 0 | 0 | 0 | 0 | |
| 2720 | 0 | 121 | 0 | 329120 | |
| 2730 | 0 | 0 | 0 | 0 | |
| 2740 | 2 | 85 | 5480 | 232900 | |
| 2750 | 2 | 0 | 5500 | 0 | |
| 2760 | 1 | 88 | 2760 | 242880 | |
| 2770 | 0 | 0 | 0 | 0 | |
| 2780 | 0 | 36 | 0 | 100080 | |
| | | | | | |
| | | | | | |
| | | | 3869290 | 3913980 | -1.1418 |

Table B.16: Healthcare System 6, before and after improvement

| Energy Consumption kwh | Bin size after improvement | Bin size before improvement | Total EC after | Total EC before | Net Difference |
|---|---|---|---|---|---|
| 3380 | 1 | 0 | 3380 | 0 | |
| 3390 | 0 | 0 | 0 | 0 | |
| 3395 | 0 | 0 | 0 | 0 | |
| 3400 | 135 | 0 | 459000 | 0 | |
| 3405 | 23 | 0 | 78315 | 0 | |
| 3410 | 20 | 1 | 68200 | 3410 | |
| 3415 | 1 | 0 | 3415 | 0 | |
| 3420 | 117 | 118 | 400140 | 403560 | |
| 3425 | 142 | 0 | 486350 | 0 | |
| 3430 | 45 | 12 | 154350 | 41160 | |
| 3435 | 37 | 0 | 127095 | 0 | |
| 3440 | 33 | 252 | 113520 | 866880 | |
| 3445 | 90 | 0 | 310050 | 0 | |
| 3450 | 45 | 47 | 155250 | 162150 | |
| 3455 | 31 | 0 | 107105 | 0 | |
| 3460 | 17 | 51 | 58820 | 176460 | |
| 3465 | 35 | 0 | 121275 | 0 | |
| 3470 | 97 | 21 | 336590 | 72870 | |
| 3475 | 49 | 0 | 170275 | 0 | |
| 3480 | 30 | 7 | 104400 | 24360 | |
| 3485 | 42 | 0 | 146370 | 0 | |
| 3490 | 36 | 25 | 125640 | 87250 | |
| 3495 | 23 | 0 | 80385 | 0 | |
| 3500 | 53 | 101 | 185500 | 353500 | |
| 3505 | 34 | 0 | 119170 | 0 | |
| 3510 | 35 | 98 | 122850 | 343980 | |
| 3515 | 46 | 0 | 161690 | 0 | |
| 3520 | 94 | 70 | 330880 | 246400 | |
| 3525 | 18 | 0 | 63450 | 0 | |
| 3530 | 66 | 117 | 232980 | 413010 | |
| 3535 | 26 | 0 | 91910 | 0 | |
| 3540 | 46 | 48 | 162840 | 169920 | |
| 3545 | 3 | 0 | 10635 | 0 | |
| 3550 | 26 | 35 | 92300 | 124250 | |

Table B.16 continued

| | | | | | |
|---|---|---|---|---|---|
| 3555 | 3 | 0 | 10665 | 0 | |
| 3560 | 2 | 43 | 7120 | 153080 | |
| 3565 | 0 | 0 | 0 | 0 | |
| 3570 | 0 | 57 | 0 | 203490 | |
| 3575 | 0 | 0 | 0 | 0 | |
| 3580 | 0 | 16 | 0 | 57280 | |
| 3585 | 0 | 0 | 0 | 0 | |
| 3590 | 0 | 111 | 0 | 398490 | |
| 3595 | 0 | 0 | 0 | 0 | |
| 3600 | 0 | 106 | 0 | 381600 | |
| 3605 | 0 | 0 | 0 | 0 | |
| 3610 | 0 | 48 | 0 | 173280 | |
| 3615 | 0 | 0 | 0 | 0 | |
| 3620 | 0 | 59 | 0 | 213580 | |
| 3625 | 0 | 0 | 0 | 0 | |
| 3630 | 0 | 42 | 0 | 152460 | |
| 3635 | 0 | 0 | 0 | 0 | |
| 3640 | 0 | 3 | 0 | 10920 | |
| 3645 | 0 | 0 | 0 | 0 | |
| 3650 | 0 | 12 | 0 | 43800 | |
| | | | | | |
| | | | | | |
| | | | 5201915 | 5277140 | -1.4254880 |

# APPENDIX C

# UNCERTAINTY CHARTS AND SENSITIVITY ANALYSIS CHARTS

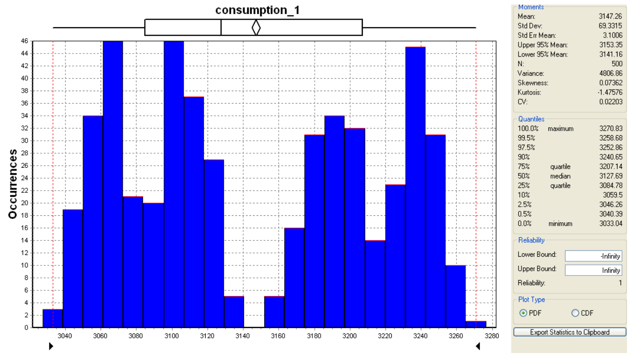


Figure C.1: Office System 1; Energy Consumption @ first year; Mean 0.75

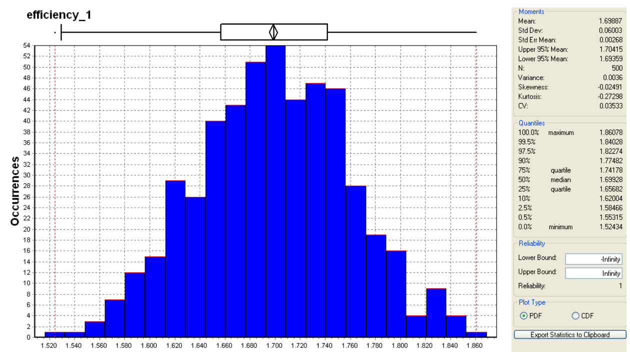


Figure C.2: Office System 1; Energy Efficiency @ first year; Mean 0.75

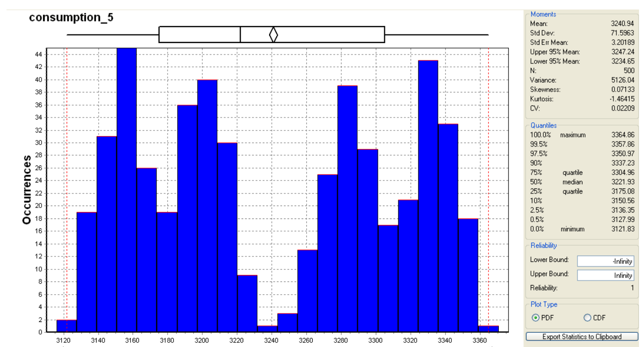


Figure C.3: Office System 1; Energy Consumption @ 5 years average; Mean 0.75

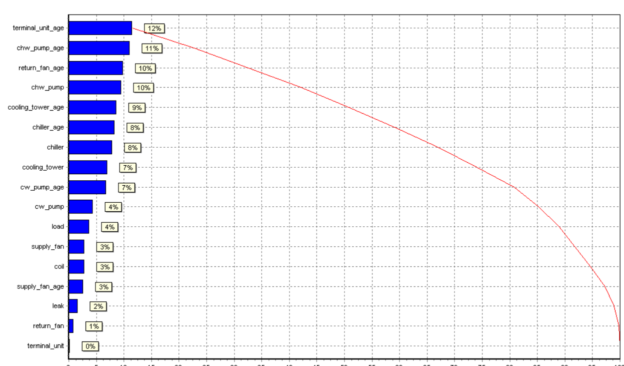


Figure C.4: Office System 1; Sensitivity analysis results; Mean 0.75

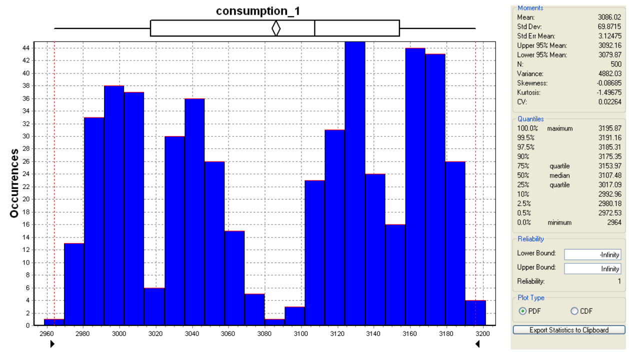

Figure C.5; Office System 1; Energy Consumption @ first year; Mean 0.5

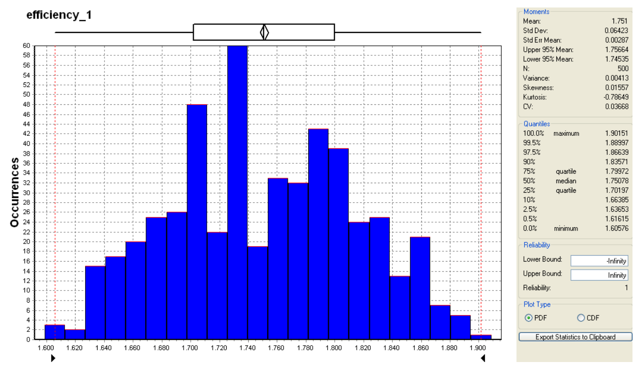

Figure C.6; Office System 1; Energy Efficiency @ first year; Mean 0.5

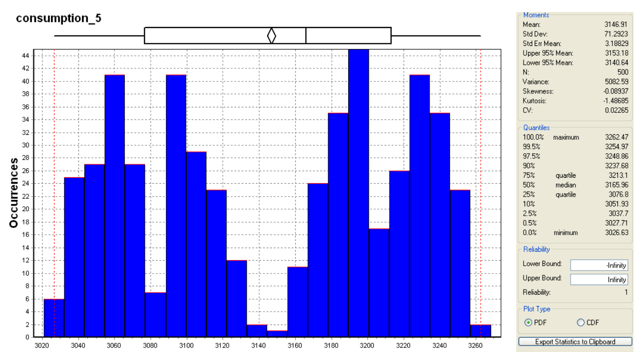

Figure C.7; Office System 1; Energy Consumption @ 5 years average; Mean 0.5

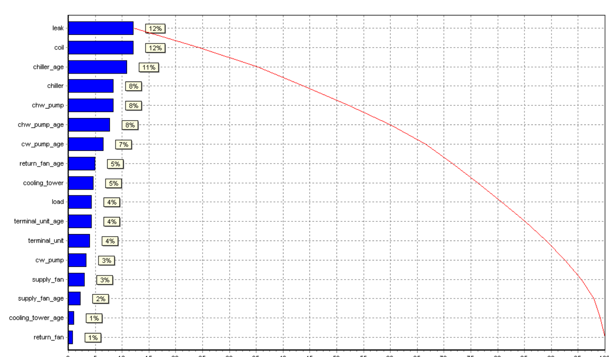

Figure C.8; Office System 1; Sensitivity analysis results; Mean 0.5

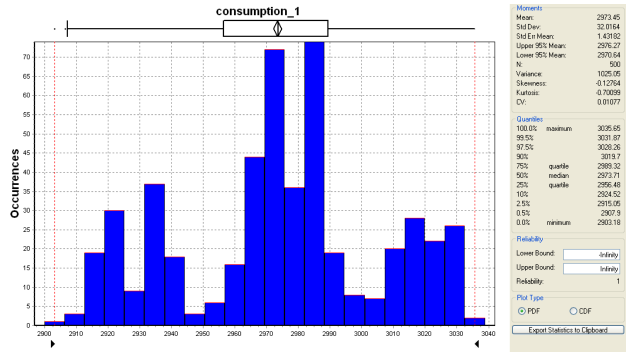


Figure C.9; Office System 1; Energy Consumption @ first year; Mean 0.25

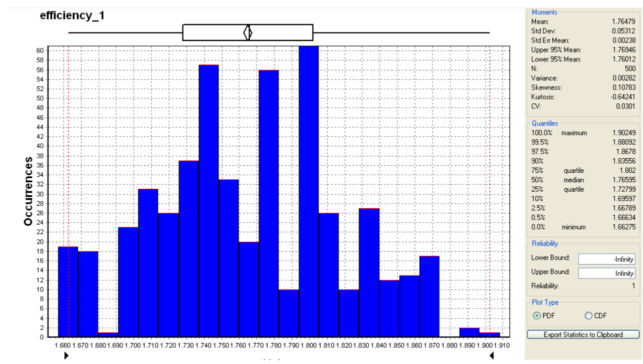


Figure C.10; Office System 1; Energy Efficiency @ first year; Mean 0.25

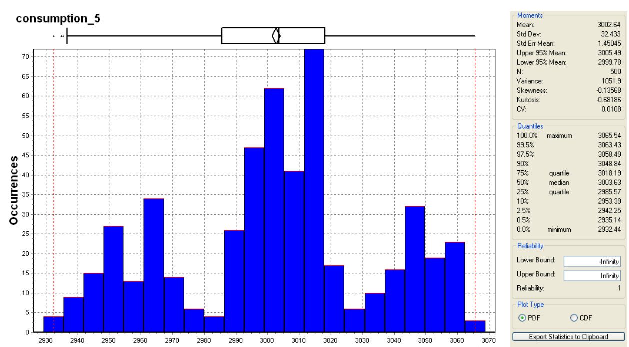


Figure C.11; Office System 1; Energy Consumption @ 5 years average; Mean 0.25

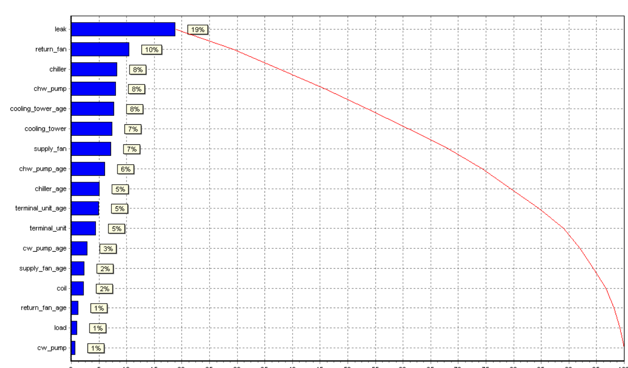


Figure C.12; Office System 1; Sensitivity analysis results; Mean 0.25

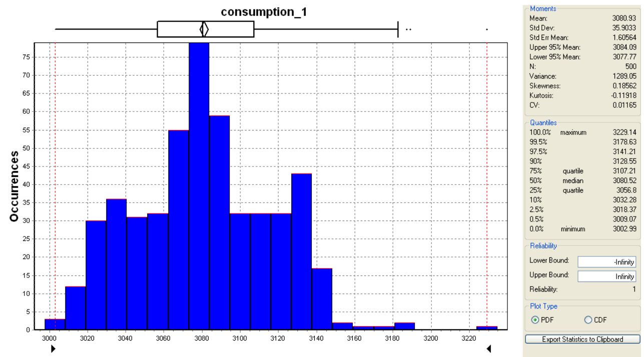


Figure C.13; Office Improved System 1; Energy Consumption @ first year; Mean 0.75

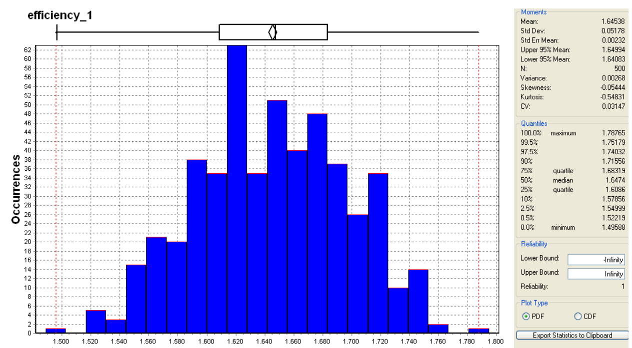


Figure C.14; Office Improved System 1; Energy Efficiency @ first year; Mean 0.75

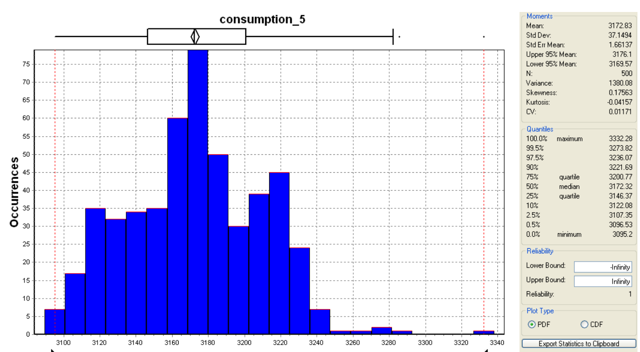


Figure C.15; Office Improved System 1; Energy Consumption @ 5 years average; Mean 0.75

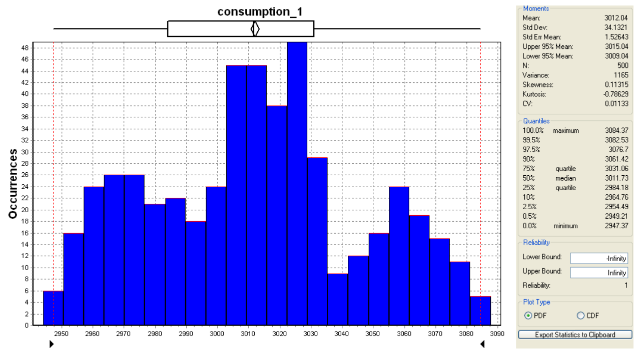

Figure C.16; Office Improved System 1; Energy Consumption @ first year; Mean 0.5

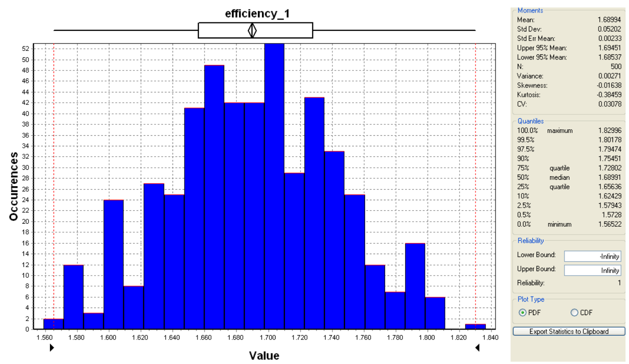

Figure C.17; Office Improved System 1; Energy Efficiency @ first year; Mean 0.5

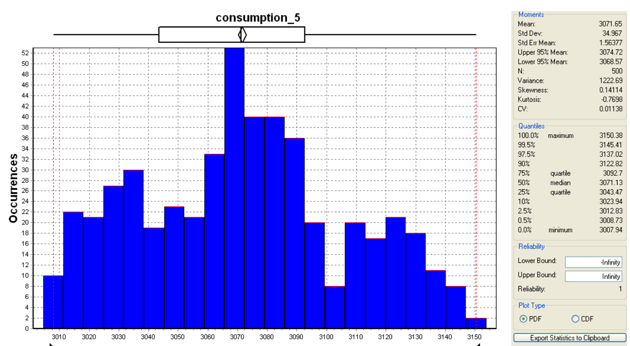

Figure C.18; Office Improved System 1; Energy Consumption @ 5 years average; Mean 0.5

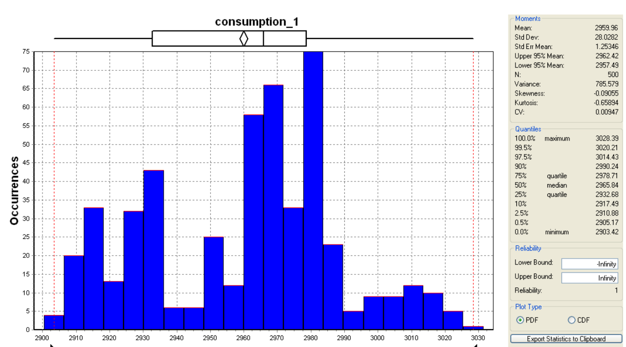

Figure C.19; Office Improved System 1; Energy Consumption @ first year; Mean 0.25

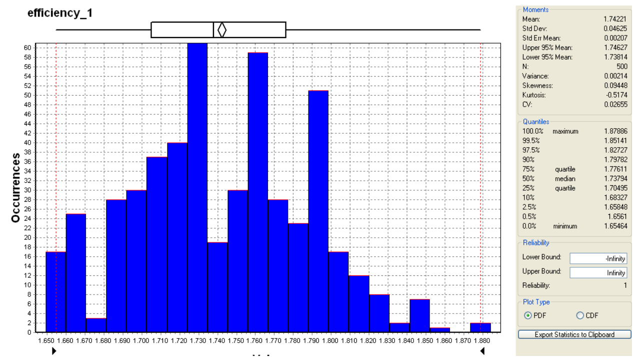


Figure C.20; Office Improved System 1; Energy Efficiency @ first year; Mean 0.25

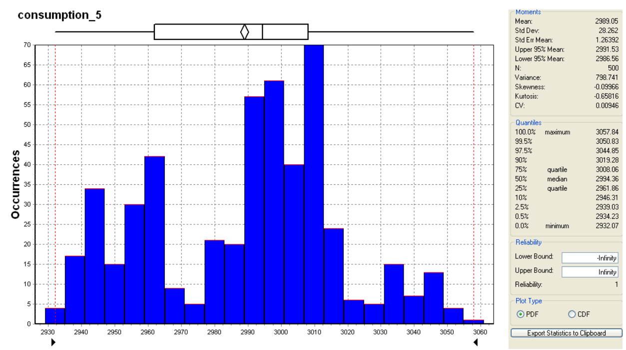


Figure C.21; Office Improved System 1; Energy Consumption @ 5 years average; Mean 0.25

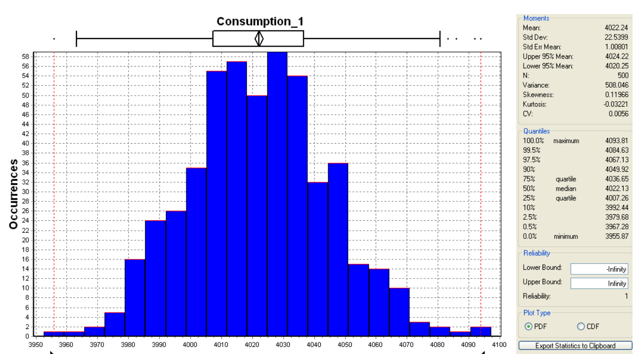


Figure C.22; Office System 2; Energy Consumption @ first year; Mean 0.75

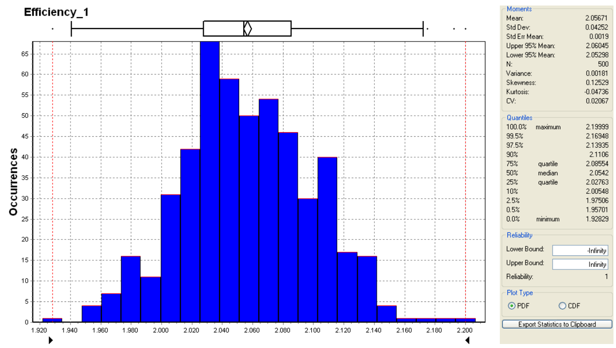


Figure C.23; Office System 2; Energy Efficiency @ first year; Mean 0.75

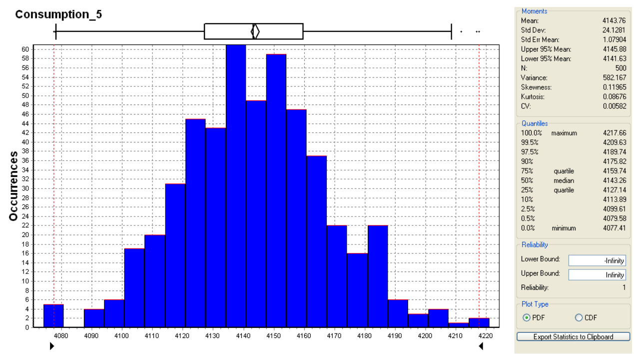


Figure C.24; Office System 2; Energy Consumption @ 5 years average; Mean 0.75

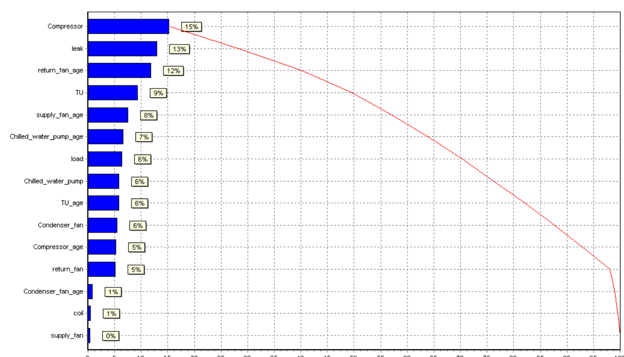


Figure C.25; Office System 2; Sensitivity analysis results; Mean 0.75

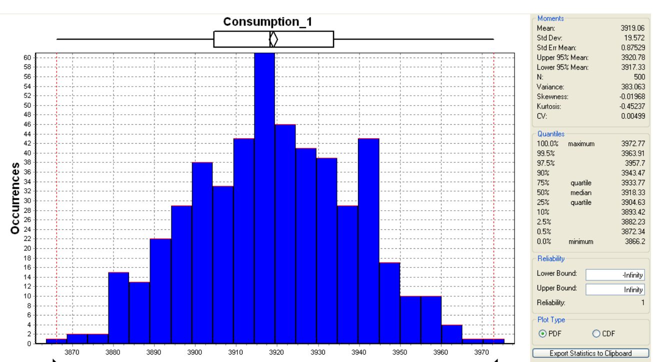


Figure C.26; Office System 2; Energy Consumption @ first year; Mean 0.5

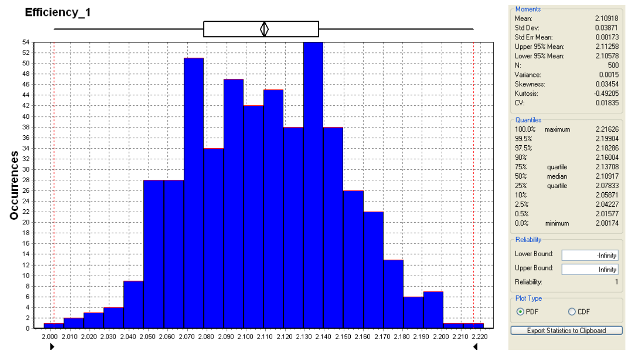

Figure C.27; Office System 2; Energy Efficiency @ first year; Mean 0.5

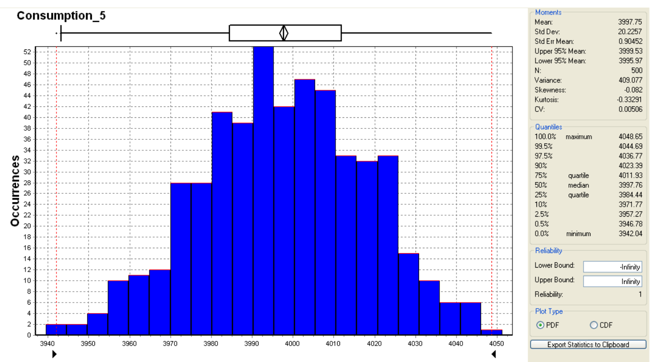

Figure C.28; Office System 2; Energy Consumption @ 5 years average; Mean 0.5

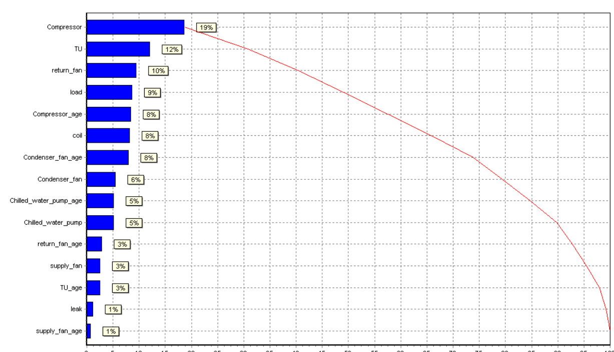

Figure C.29; Office System 2; Sensitivity analysis results; Mean 0.5

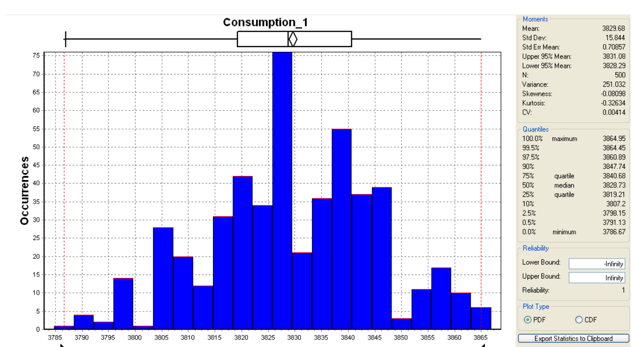

Figure C.30; Office System 2; Energy Consumption @ first year; Mean 0.25

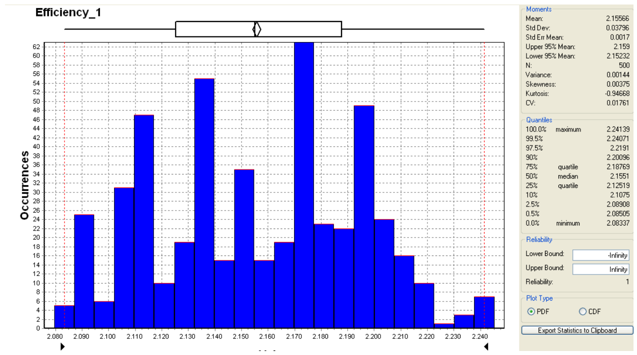

Figure C.31; Office System 2; Energy Efficiency @ first year; Mean 0.25

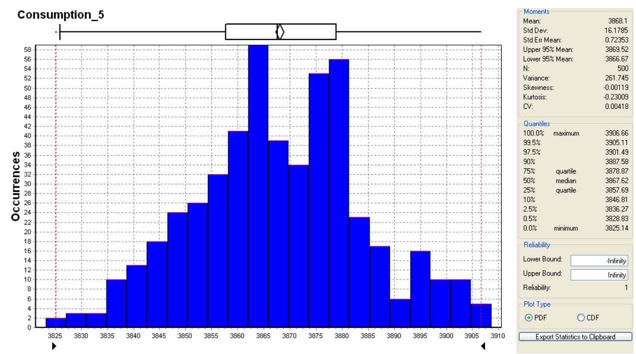

Figure C.32; Office System 2; Energy Consumption @ 5 years average; Mean 0.25

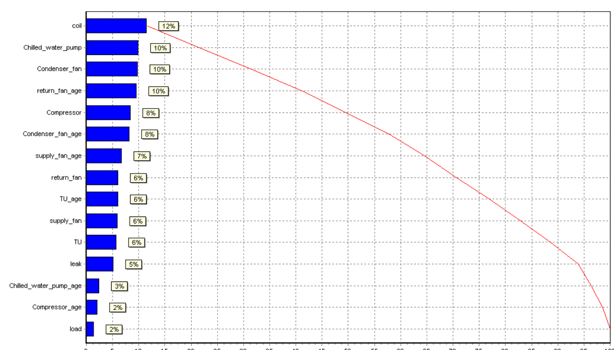

Figure C.33; Office System 2; Sensitivity analysis results; Mean 0.25

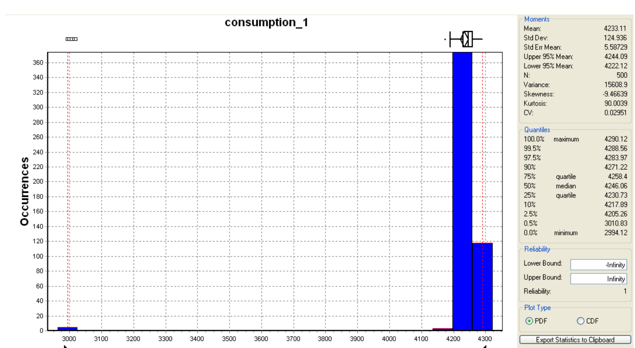

Figure C.34; Office System 3; Energy Consumption @ first year; Mean 0.75

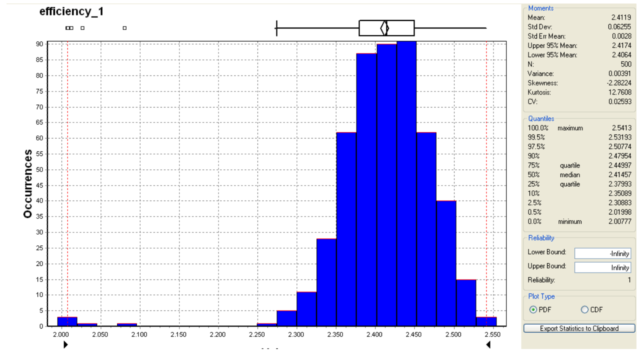

Figure C.35; Office System 3; Energy Efficiency @ first year; Mean 0.75

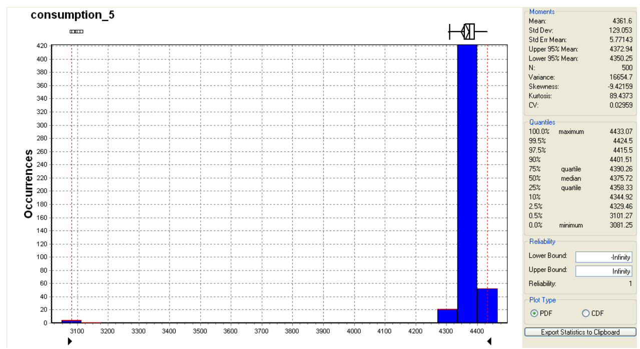

Figure C.36; Office System 3; Energy Consumption @ 5 years average; Mean 0.75

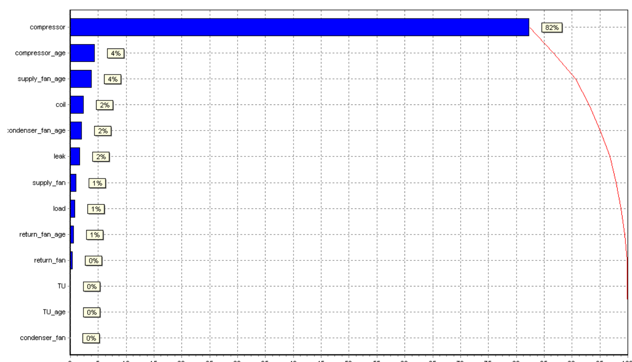

Figure C.37; Office System 3; Sensitivity analysis results; Mean 0.75

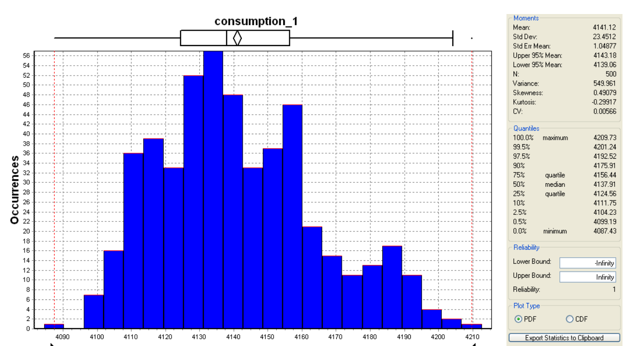

Figure C.38; Office System 3; Energy Consumption @ first year; Mean 0.5

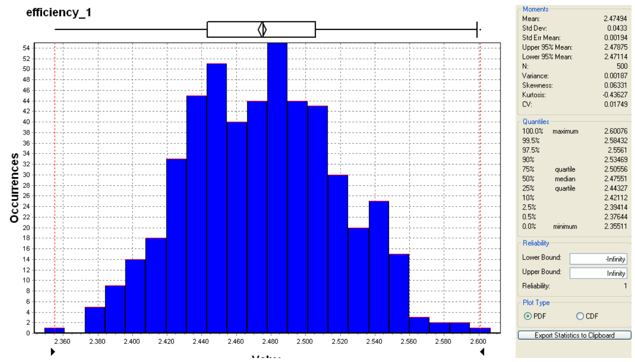


Figure C.39; Office System 3; Energy Efficiency @ first year; Mean 0.5

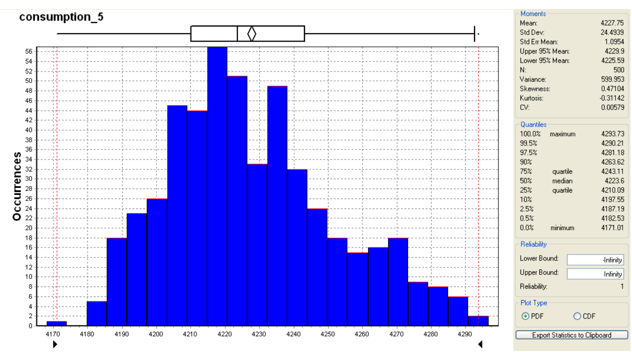


Figure C.40; Office System 3; Energy Consumption @ 5 years average; Mean 0.5

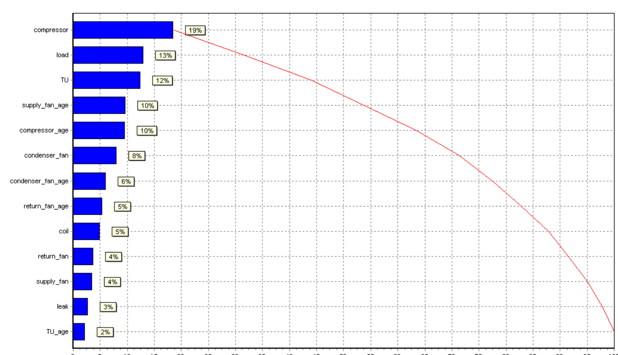


Figure C.41; Office System 3; Sensitivity analysis results; Mean 0.5

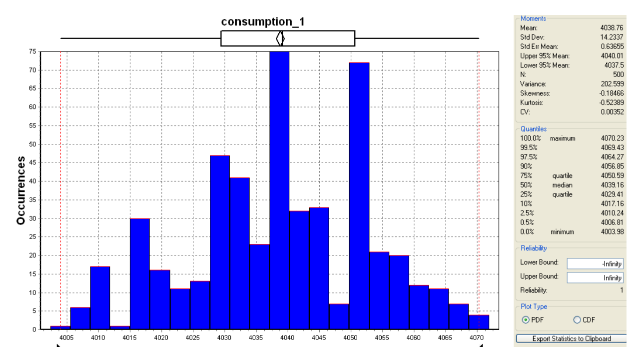


Figure C.42; Office System 3; Energy Consumption @ first year; Mean 0.25

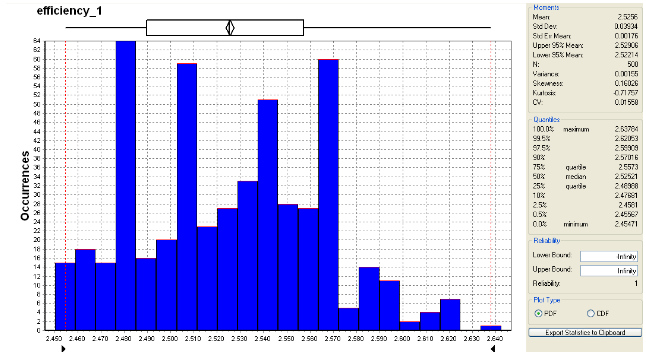


Figure C.43; Office System 3; Energy Efficiency @ first year; Mean 0.25

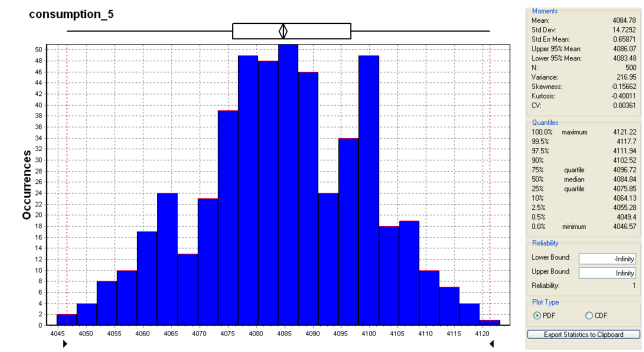


Figure C.44; Office System 3; Energy Consumption @ 5 years average; Mean 0.25

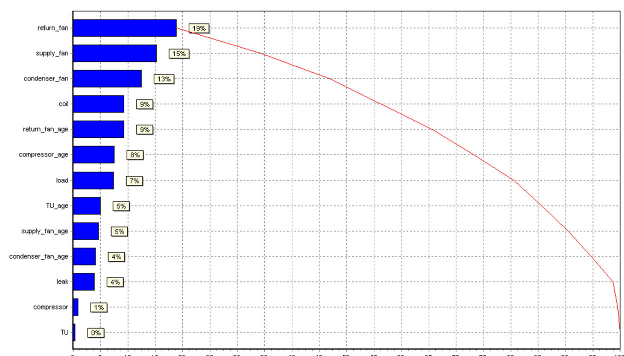


Figure C.45; Office System 3; Sensitivity analysis results; Mean 0.25

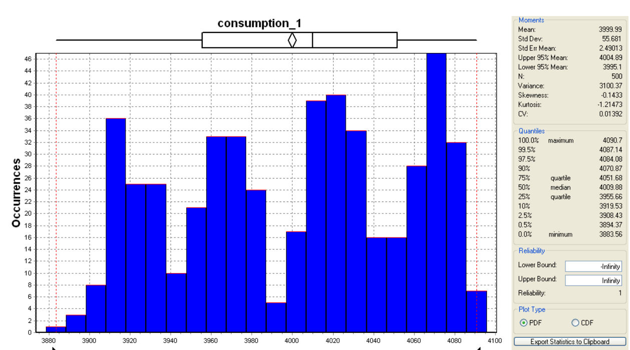


Figure C.46; Office System 4; Energy Consumption @ first year; Mean 0.75

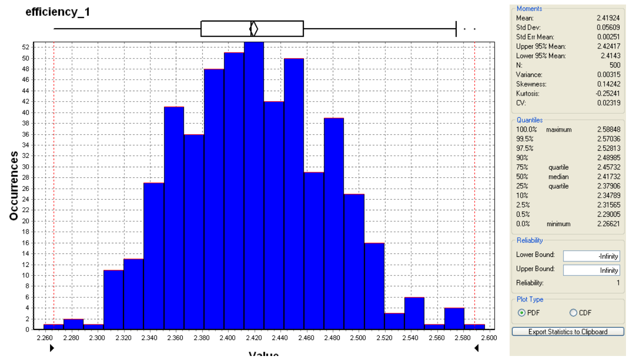


Figure C.47; Office System 4; Energy Efficiency @ first year; Mean 0.75

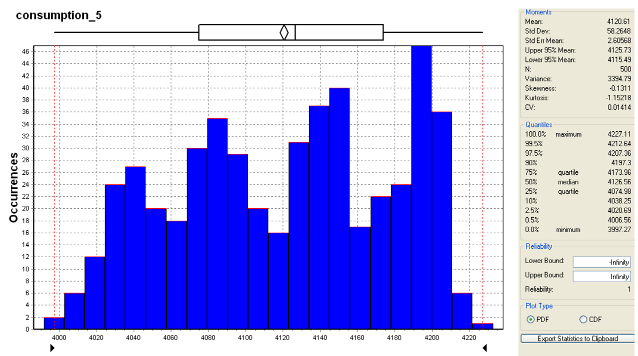


Figure C.48; Office System 4; Energy Consumption @ 5 years average; Mean 0.75

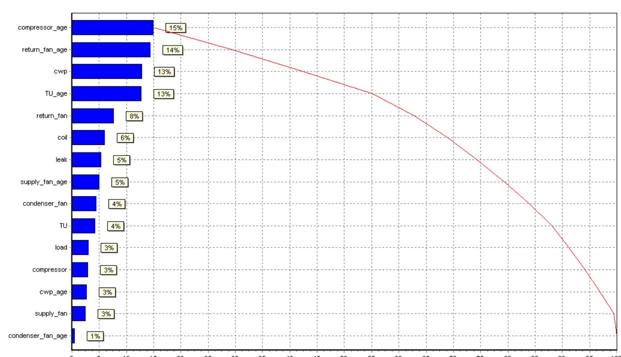


Figure C.49; Office System 4; Sensitivity analysis results; Mean 0.75

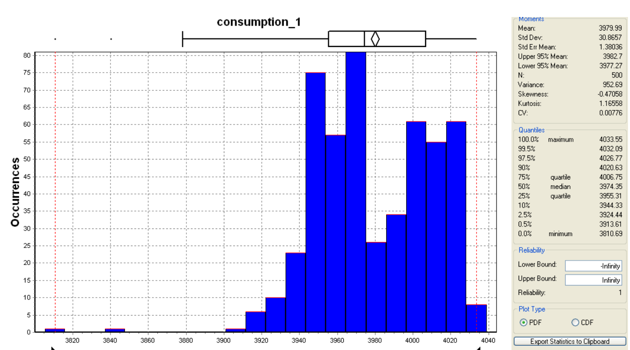


Figure C.50; Office System 4; Energy Consumption @ first year; Mean 0.5

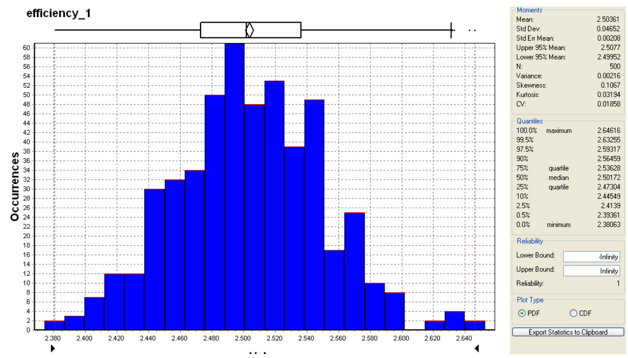

Figure C.51; Office System 4; Energy Efficiency @ first year; Mean 0.5

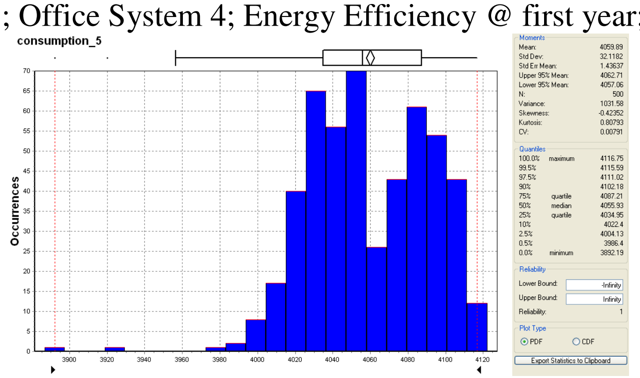

Figure C.52; Office System 4; Energy Consumption @ 5 years average; Mean 0.5

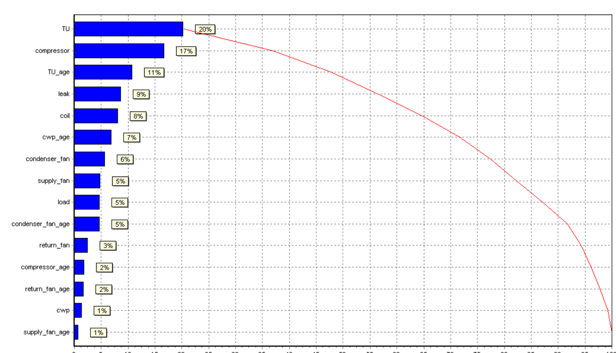
Figure C.53; Office System 4; Sensitivity analysis results; Mean 0.5

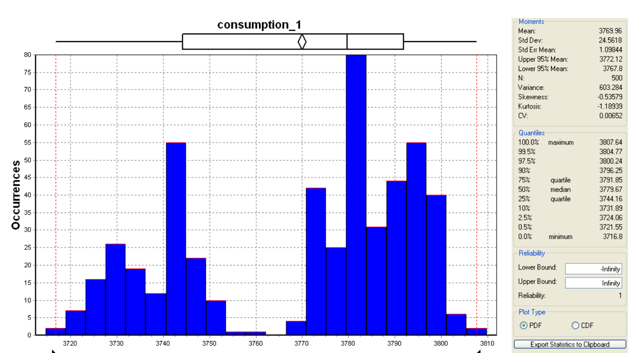

Figure C.54; Office System 4; Energy Consumption @ first year; Mean 0.25

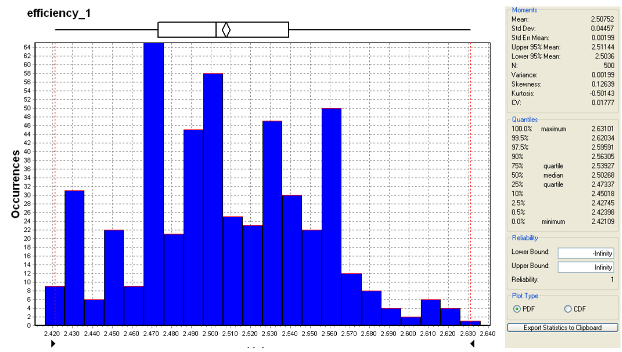


Figure C.55; Office System 4; Energy Efficiency @ first year; Mean 0.25

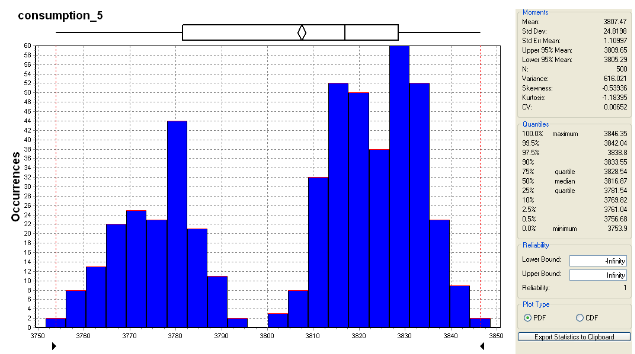


Figure C.56; Office System 4; Energy Consumption @ 5 years average; Mean 0.25

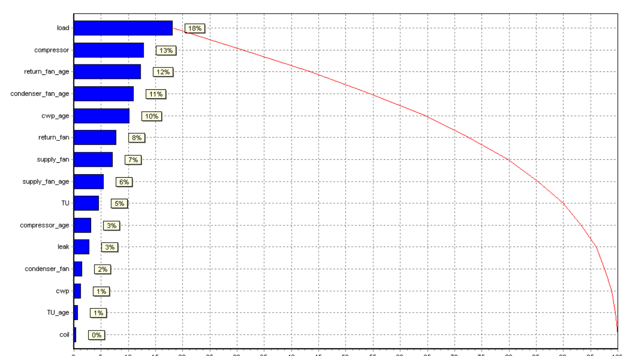

Figure C.57; Office System 4; Sensitivity analysis results; Mean 0.25

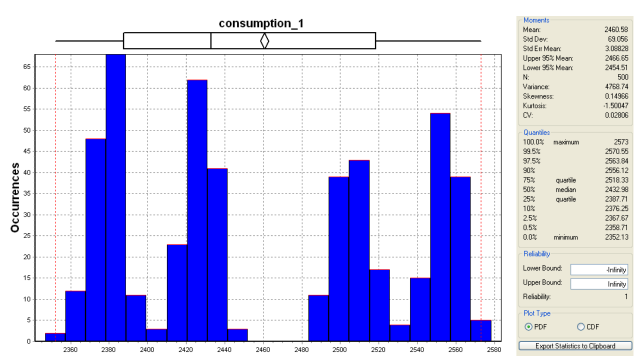


Figure C.58; Office System 5; Energy Consumption @ first year; Mean 0.75

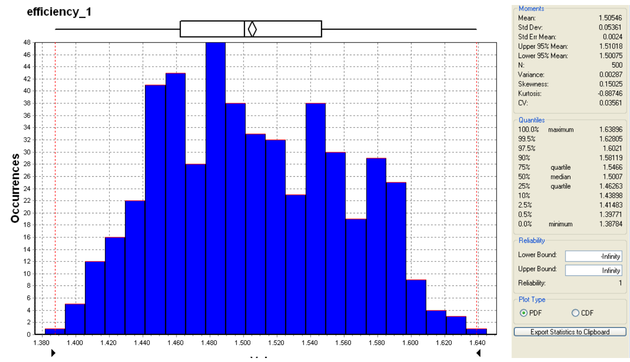


Figure C.59; Office System 5; Energy Efficiency @ first year; Mean 0.75

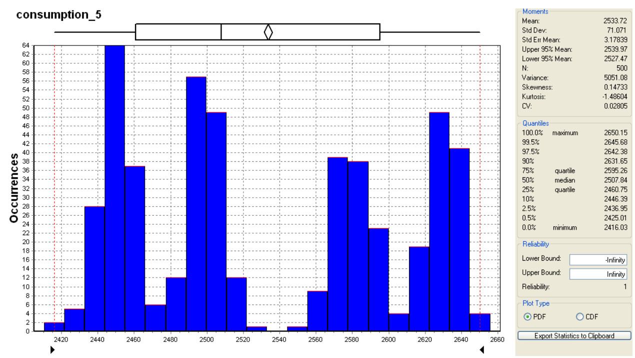


Figure C.60; Office System 5; Energy Consumption @ 5 years average; Mean 0.75

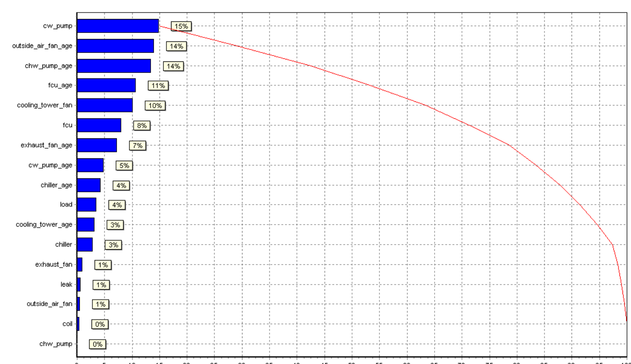


Figure C.61; Office System 5; Sensitivity analysis results; Mean 0.75

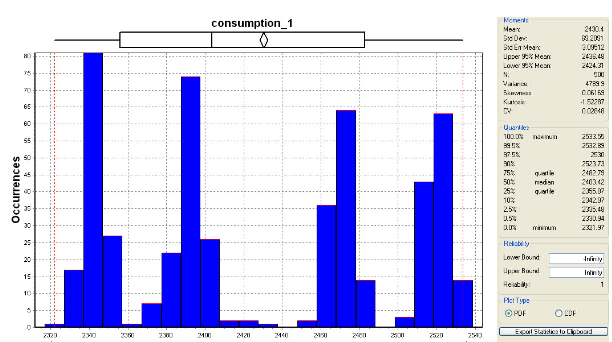


Figure C.62; Office System 5; Energy Consumption @ first year; Mean 0.5

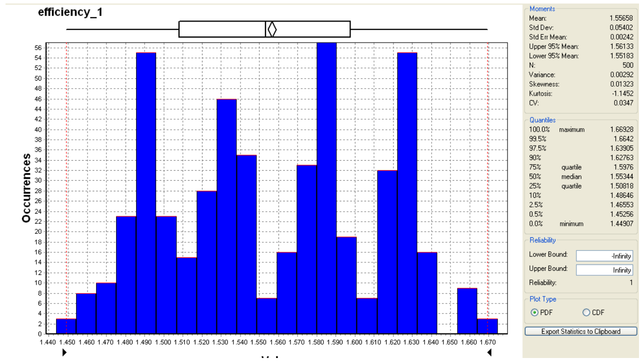

Figure C.63; Office System 5; Energy Efficiency @ first year; Mean 0.5

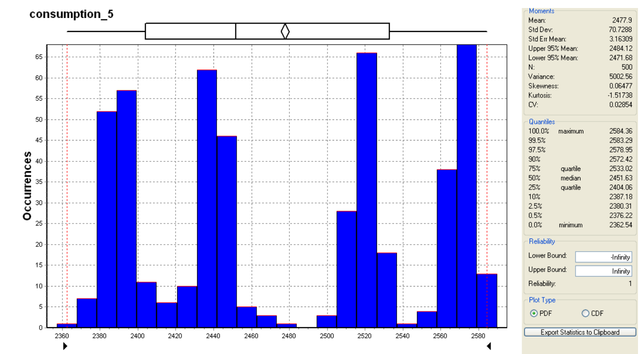

Figure C.64; Office System 5; Energy Consumption @ 5 years average; Mean 0.5

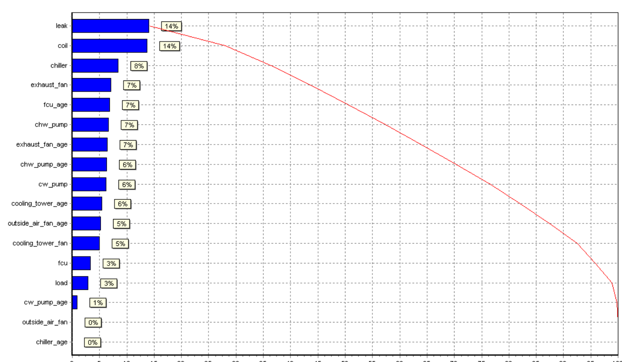

Figure C.65; Office System 5; Sensitivity analysis results; Mean 0.5

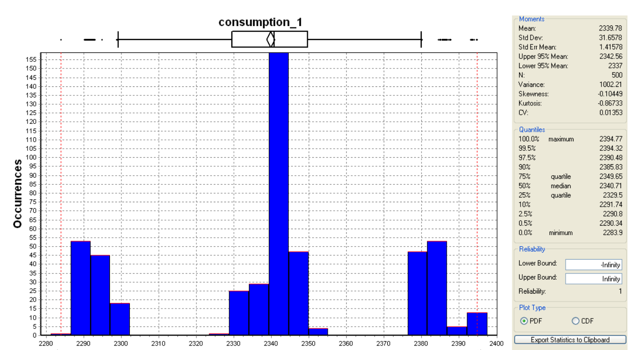

Figure C.66; Office System 5; Energy Consumption @ first year; Mean 0.25

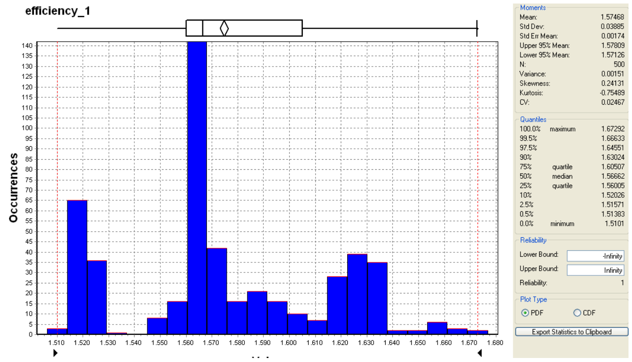


Figure C.67; Office System 5; Energy Efficiency @ first year; Mean 0.25

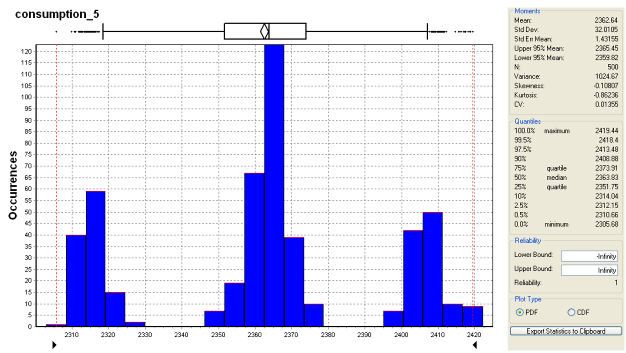


Figure C.68; Office System 5; Energy Consumption @ 5 years average; Mean 0.25

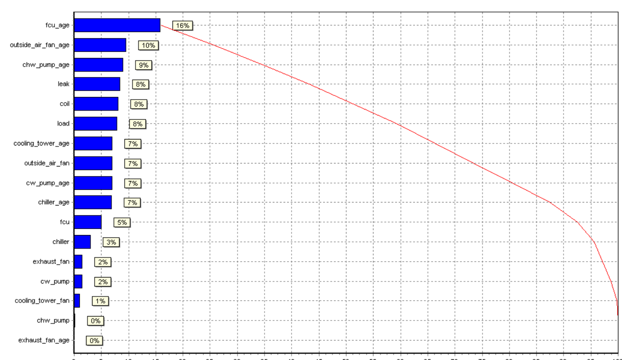


Figure C.69; Office System 5; Sensitivity analysis results; Mean 0.25

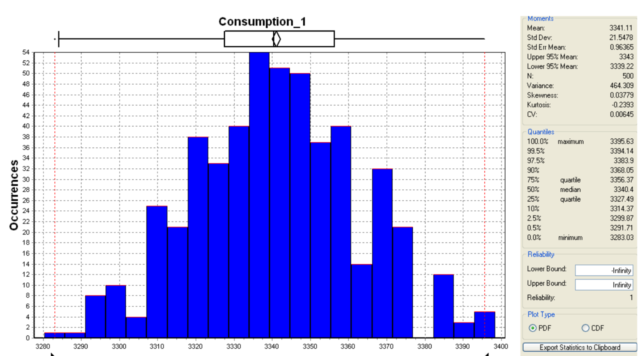


Figure C.70; Office System 6; Energy Consumption @ first year; Mean 0.75

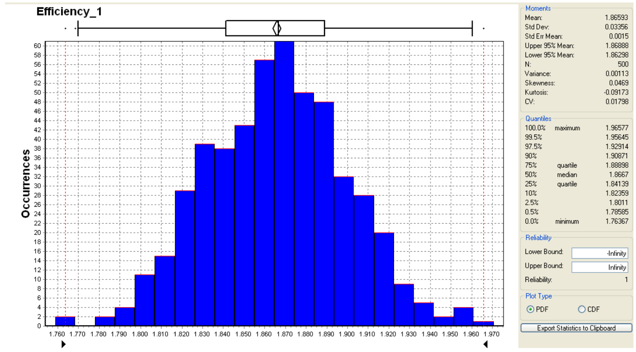

Figure C.71; Office System 6; Energy Efficiency @ first year; Mean 0.75

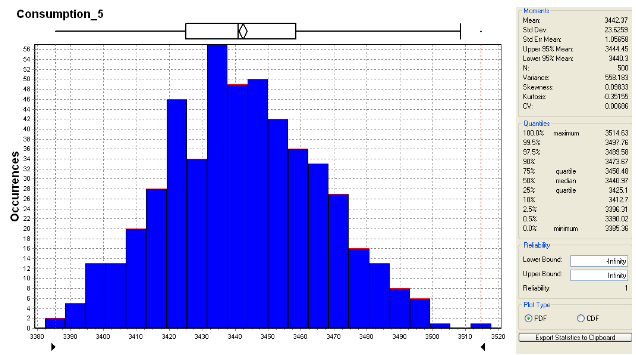

Figure C.72; Office System 6; Energy Consumption @ 5 years average; Mean 0.75

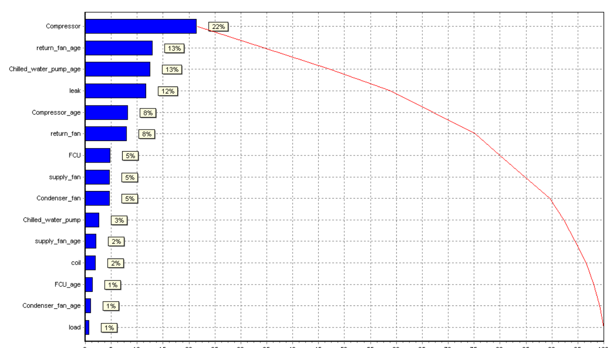

Figure C.73; Office System 6; Sensitivity analysis results; Mean 0.75

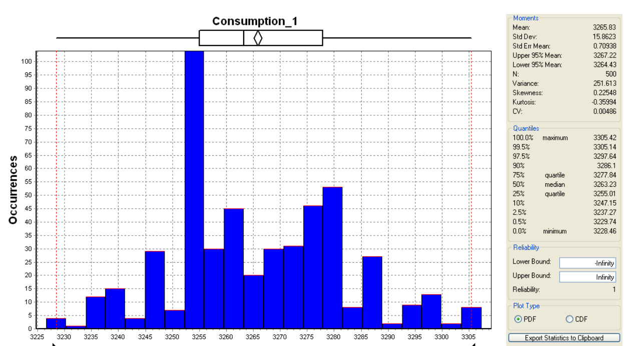

Figure C.74; Office System 6; Energy Consumption @ first year; Mean 0.5

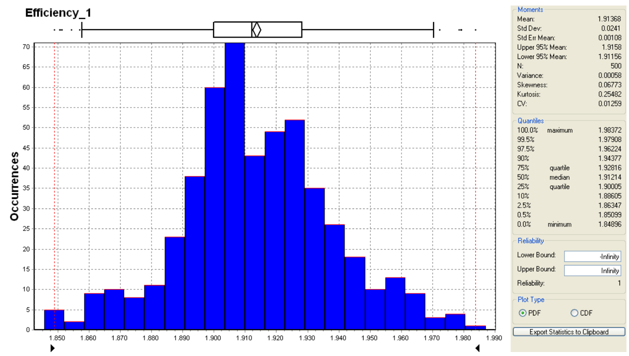

Figure C.75; Office System 6; Energy Efficiency @ first year; Mean 0.5

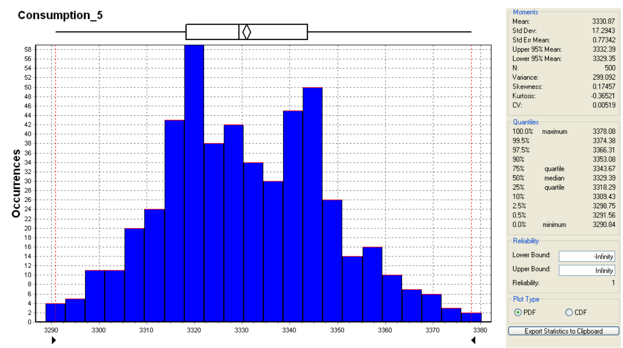

Figure C.76; Office System 6; Energy Consumption @ 5 years average; Mean 0.5

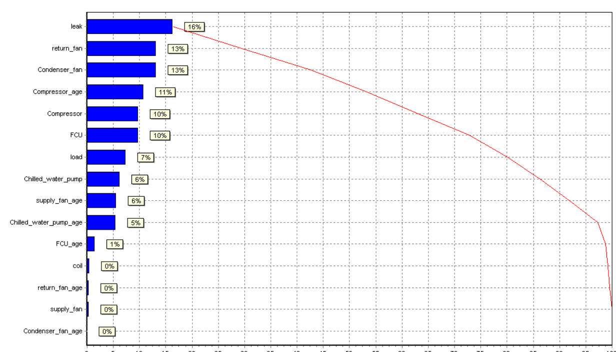

Figure C.77; Office System 6; Sensitivity analysis results; Mean 0.5

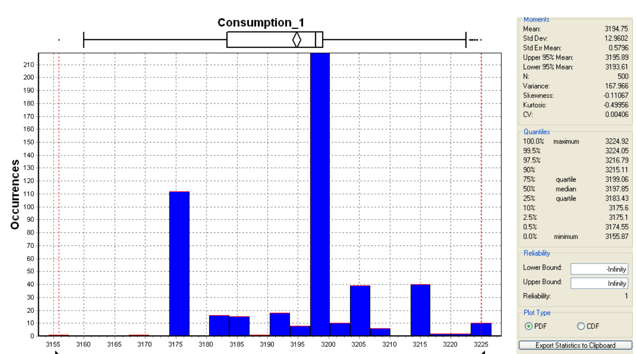

Figure C.78; Office System 6; Energy Consumption @ first year; Mean 0.25

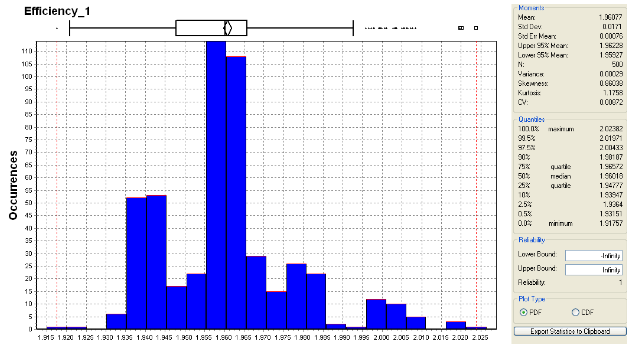

Figure C.79; Office System 6; Energy Efficiency @ first year; Mean 0.25

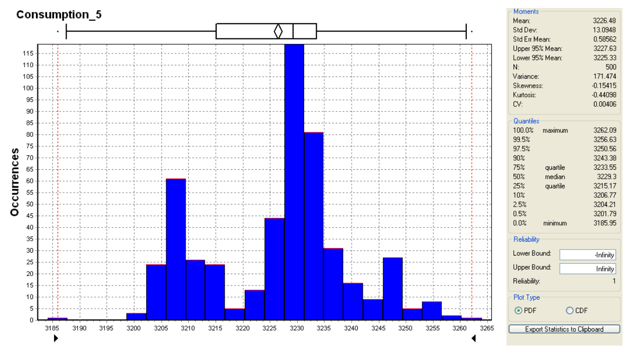

Figure C.80; Office System 6; Energy Consumption @ 5 years average; Mean 0.25

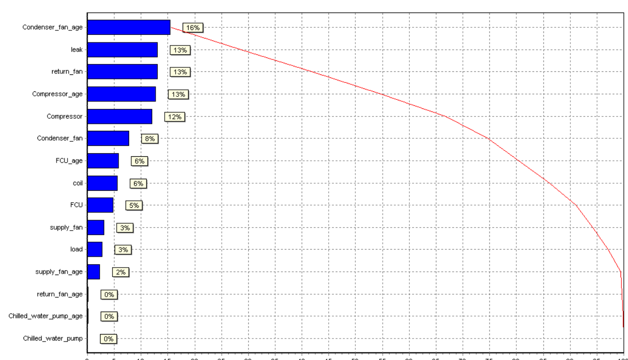

Figure C.81; Office System 6; Sensitivity analysis results; Mean 0.25

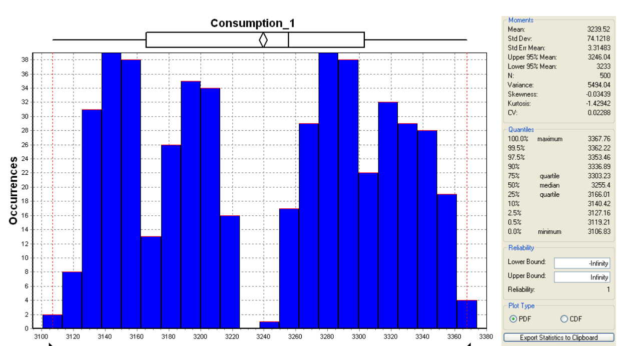

Figure C.82; Healthcare System 1; Energy Consumption @ first year; Mean 0.75

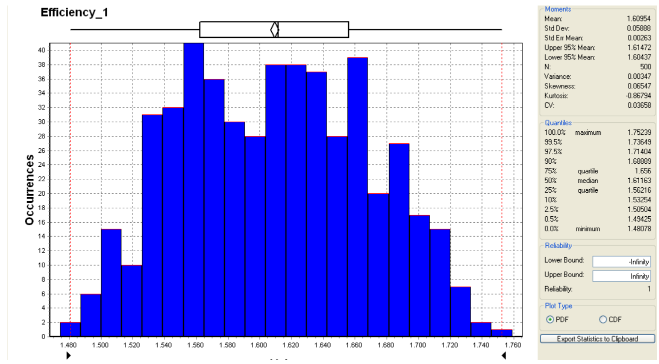


Figure C.83; Healthcare System 1; Energy Efficiency @ first year; Mean 0.75

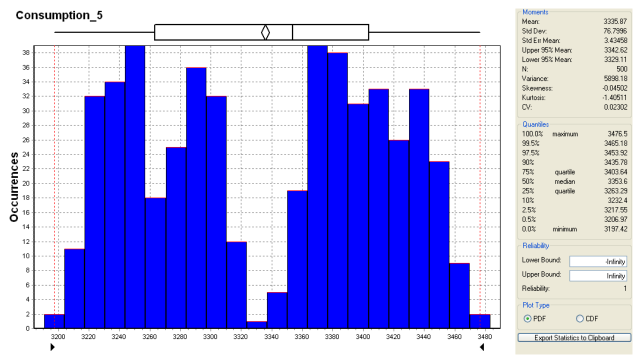


Figure C.84; Healthcare System 1; Energy Consumption @ 5 years average; Mean 0.75

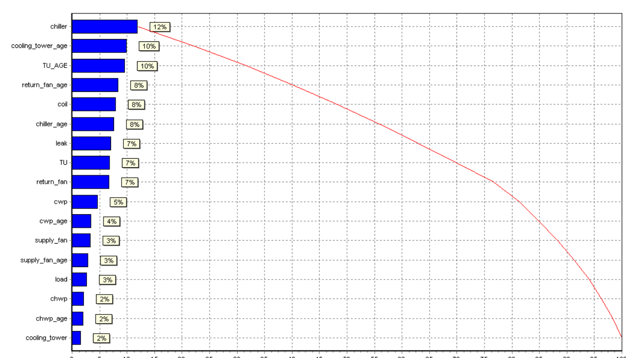

Figure C.85; Healthcare System 1; Sensitivity analysis results; Mean 0.75

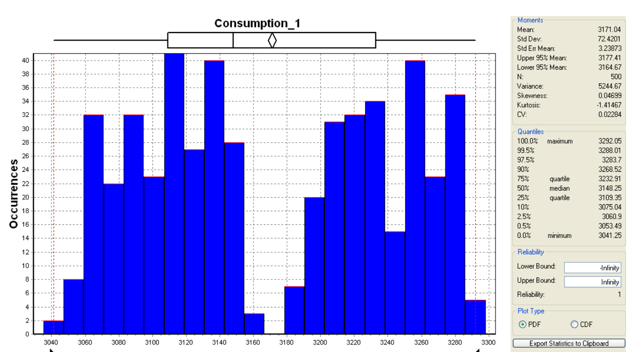


Figure C.86; Healthcare System 1; Energy Consumption @ first year; Mean 0.5

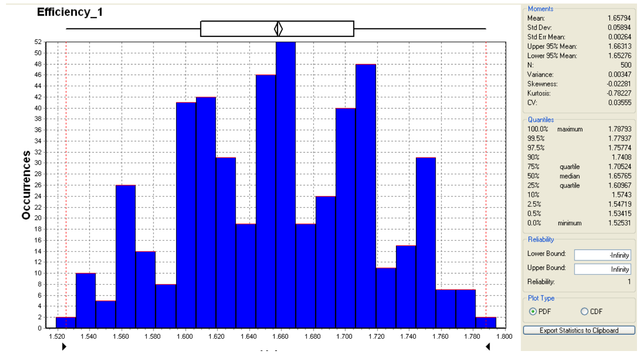


Figure C.87; Healthcare System 1; Energy Efficiency @ first year; Mean 0.5

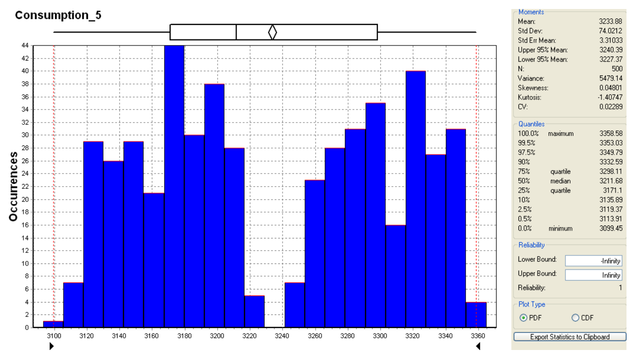


Figure C.88; Healthcare System 1; Energy Consumption @ 5 years average; Mean 0.5

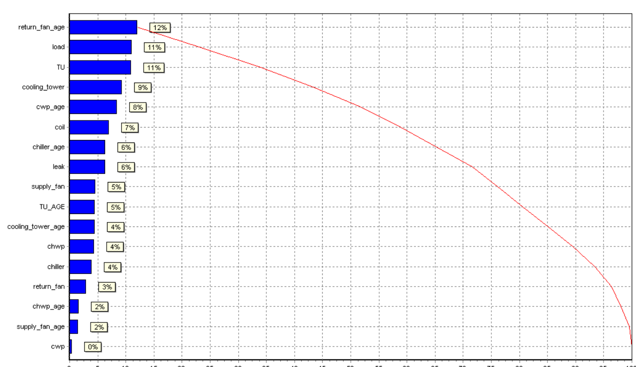


Figure C.89; Healthcare System 1; Sensitivity analysis results; Mean 0.5

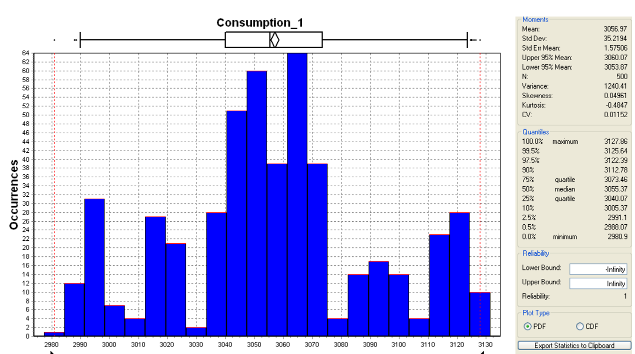


Figure C.90; Healthcare System 1; Energy Consumption @ first year; Mean 0.25

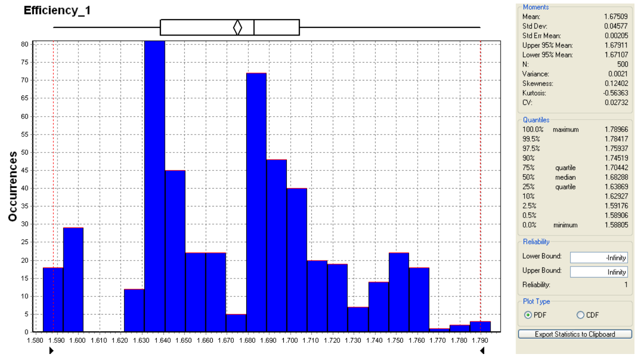

Figure C.91; Healthcare System 1; Energy Efficiency @ first year; Mean 0.25

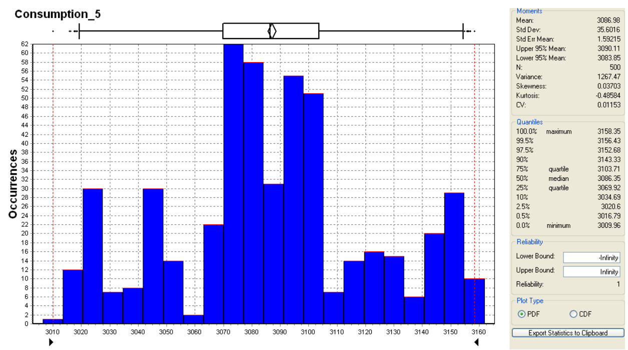

Figure C.92; Healthcare System 1; Energy Consumption @ 5 years average; Mean 0.25

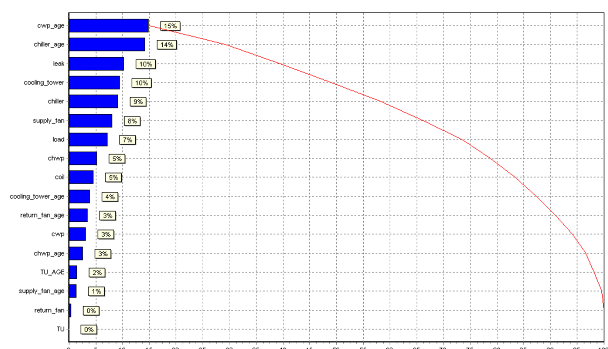

Figure C.93; Healthcare System 1; Sensitivity analysis results; Mean 0.25

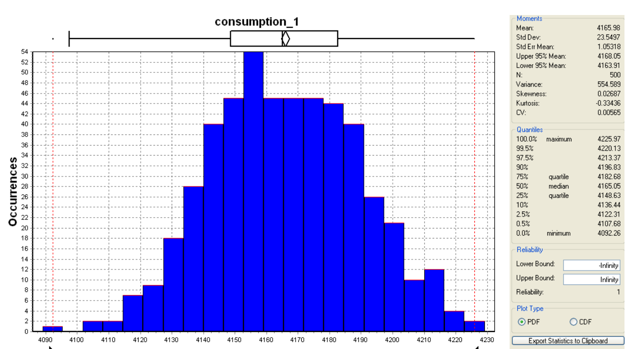

Figure C.94; Healthcare System 2; Energy Consumption @ first year; Mean 0.75

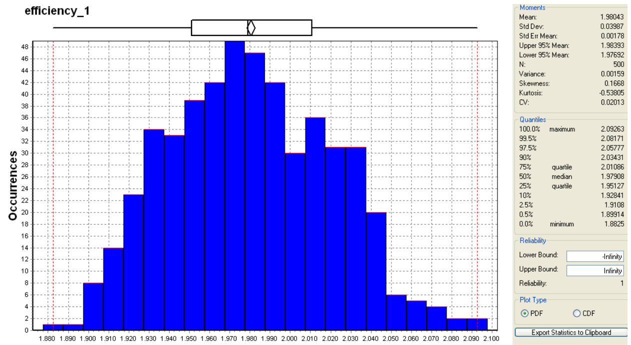


Figure C.95; Healthcare System 2; Energy Efficiency @ first year; Mean 0.75

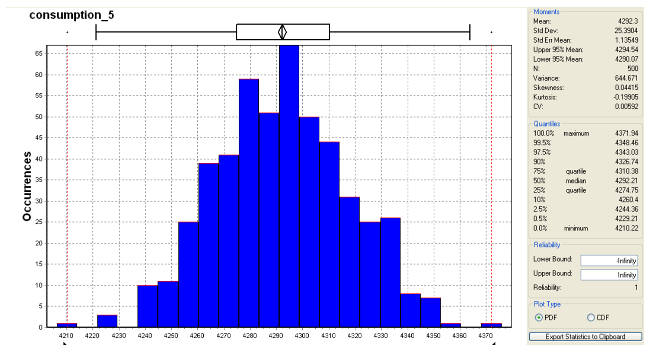


Figure C.96; Healthcare System 2; Energy Consumption @ 5 years average; Mean 0.75

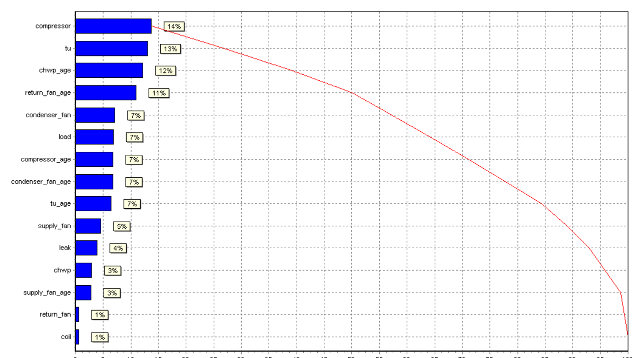


Figure C.97; Healthcare System 2; Sensitivity analysis results; Mean 0.75

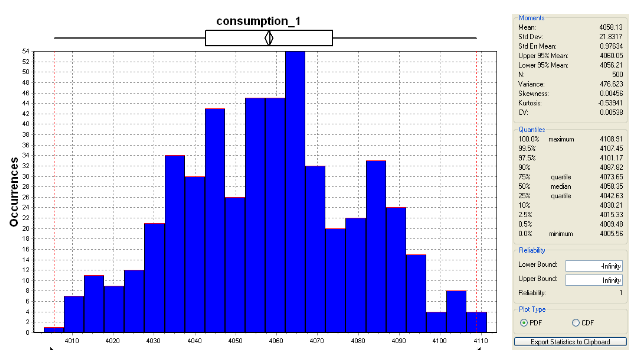


Figure C.98; Healthcare System 2; Energy Consumption @ first year; Mean 0.5

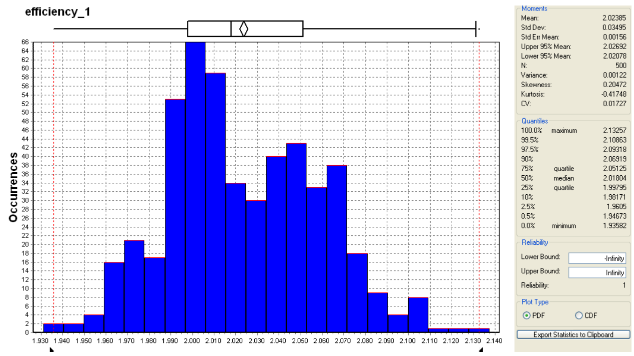


Figure C.99; Healthcare System 2; Energy Efficiency @ first year; Mean 0.5

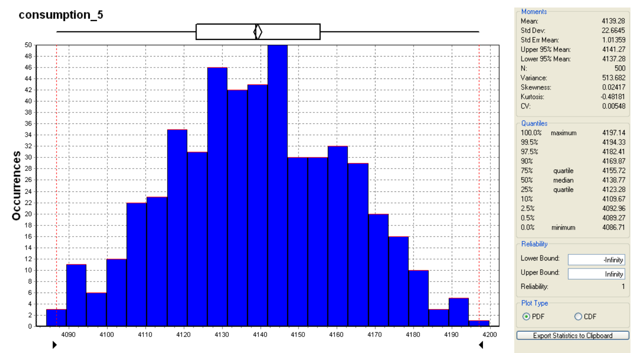


Figure C.100; Healthcare System 2; Energy Consumption @ 5 years average; Mean 0.5

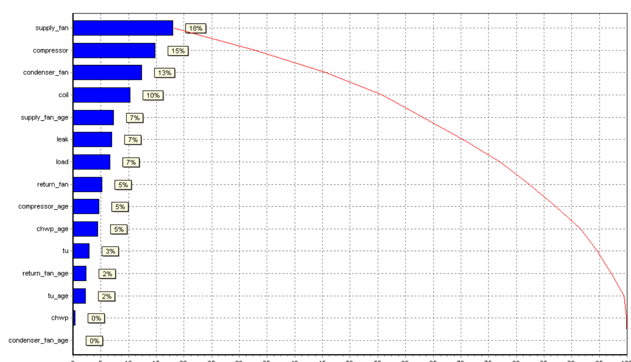


Figure C.101; Healthcare System 2; Sensitivity analysis results; Mean 0.5

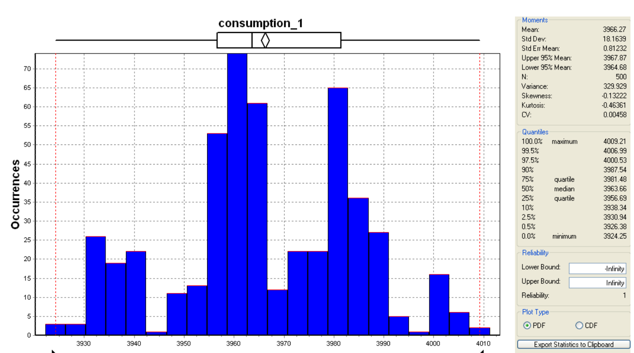


Figure C.102; Healthcare System 2; Energy Consumption @ first year; Mean 0.25

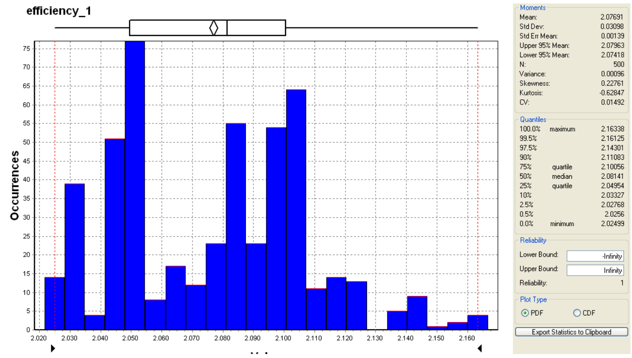


Figure C.103; Healthcare System 2; Energy Efficiency @ first year; Mean 0.25

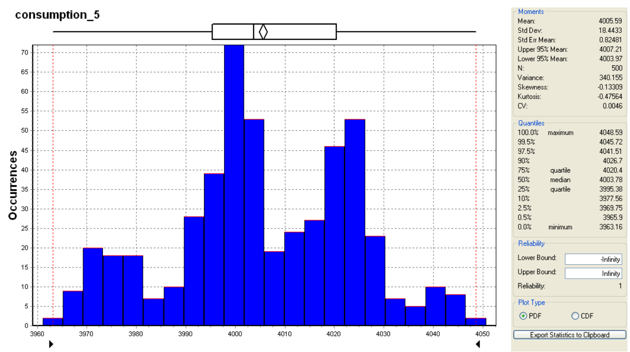


Figure C.104; Healthcare System 2; Energy Consumption @ 5 years average; Mean 0.25

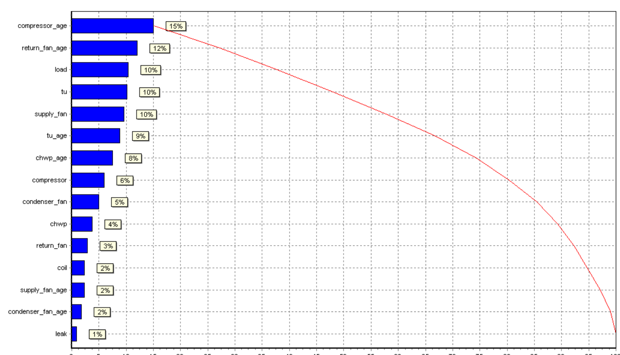


Figure C.105; Healthcare System 2; Sensitivity analysis results; Mean 0.25

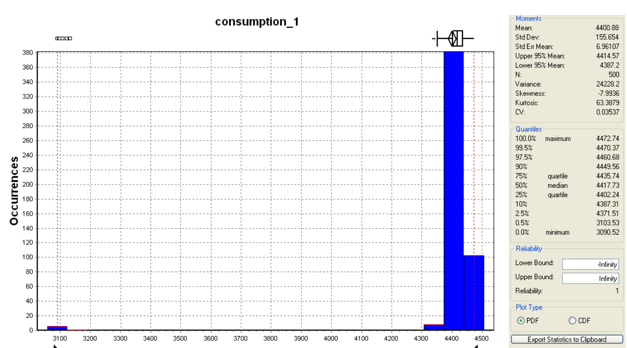


Figure C.106; Healthcare System 3; Energy Consumption @ first year; Mean 0.75

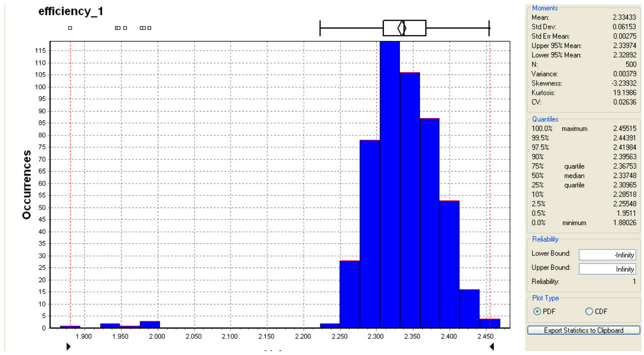

Figure C.107; Healthcare System 3; Energy Efficiency @ first year; Mean 0.75

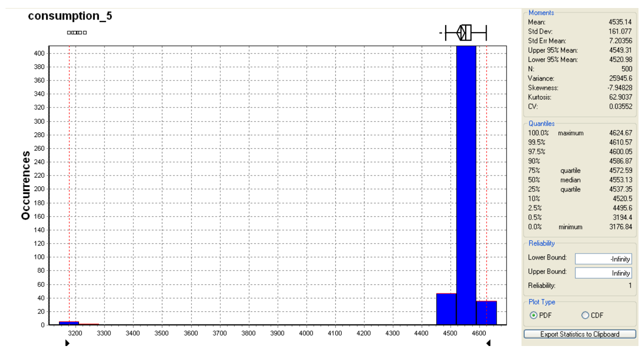

Figure C.108; Healthcare System 3; Energy Consumption @ 5 years average; Mean 0.75

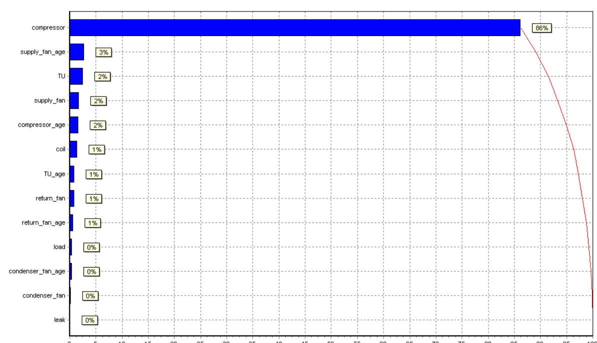

Figure C.109; Healthcare System 3; Sensitivity analysis results; Mean 0.75

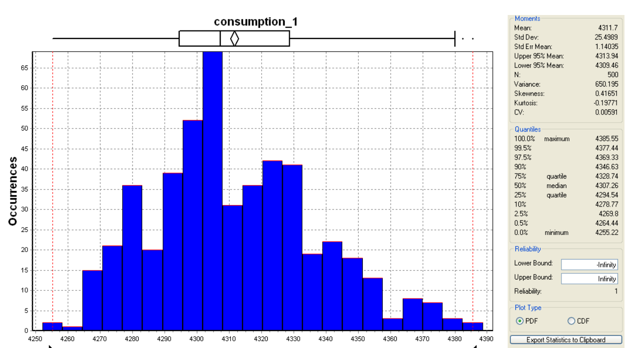

Figure C.110; Healthcare System 3; Energy Consumption @ first year; Mean 0.5

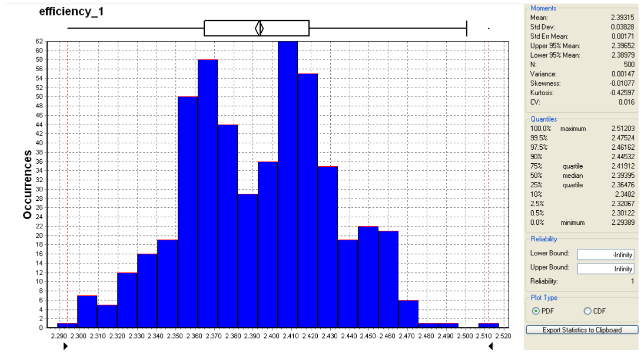

Figure C.111; Healthcare System 3; Energy Efficiency @ first year; Mean 0.5

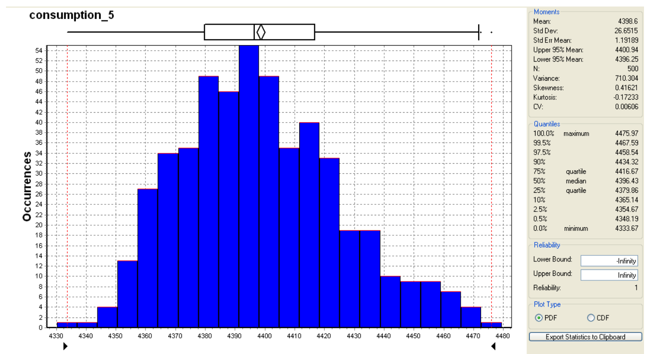

Figure C.112; Healthcare System 3; Energy Consumption @ 5 years average; Mean 0.5

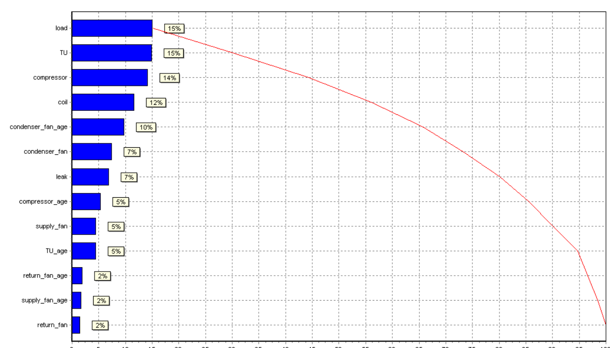

Figure C.113; Healthcare System 3; Sensitivity analysis results; Mean 0.5

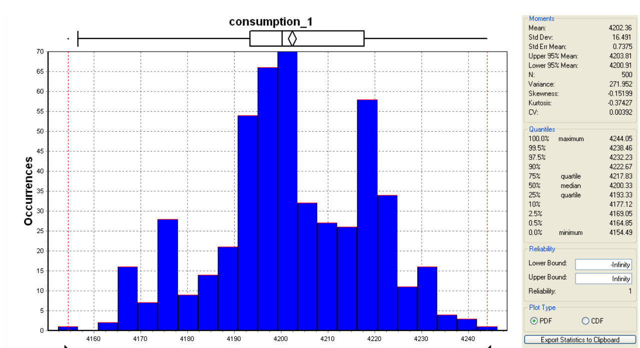

Figure C.114; Healthcare System 3; Energy Consumption @ first year; Mean 0.25

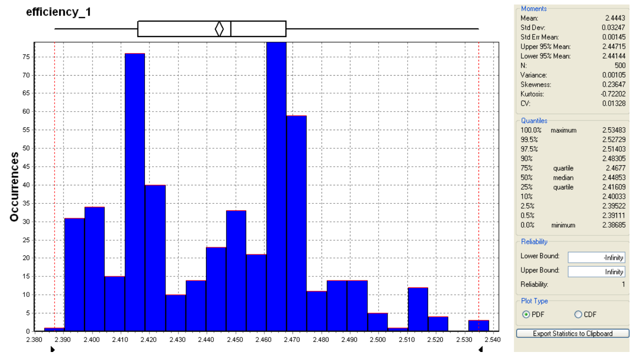

Figure C.115; Healthcare System 3; Energy Efficiency @ first year; Mean 0.25

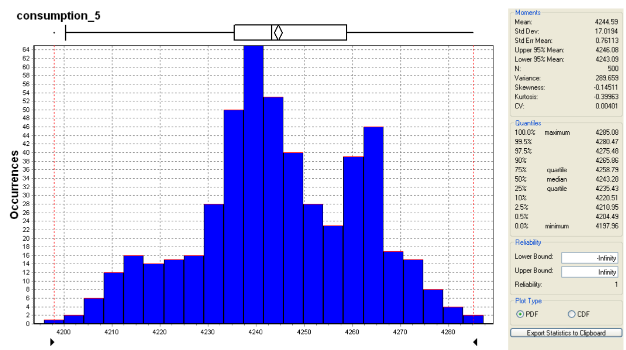

Figure C.116; Healthcare System 3; Energy Consumption @ 5 years average; Mean 0.25

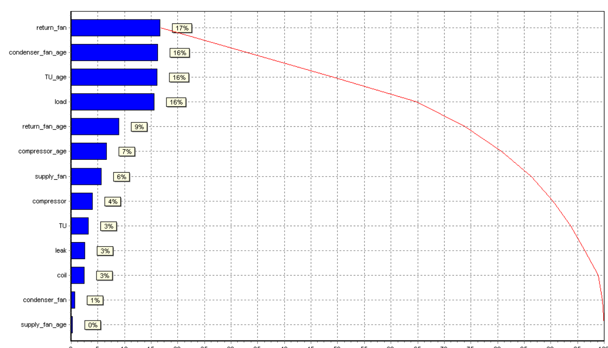

Figure C.117; Healthcare System 3; Sensitivity analysis results; Mean 0.25

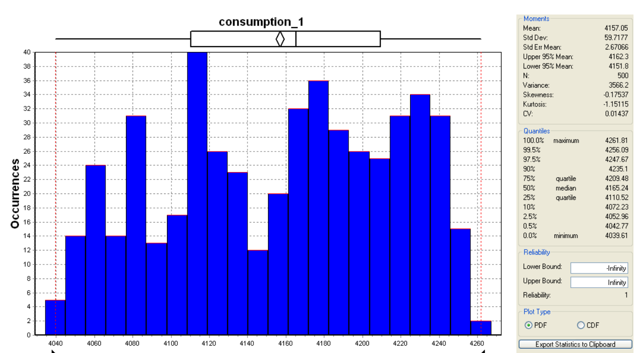

Figure C.118; Healthcare System 4; Energy Consumption @ first year; Mean 0.75

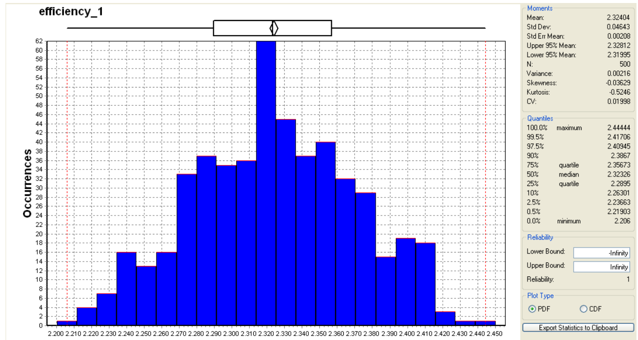

Figure C.119; Healthcare System 4; Energy Efficiency @ first year; Mean 0.75

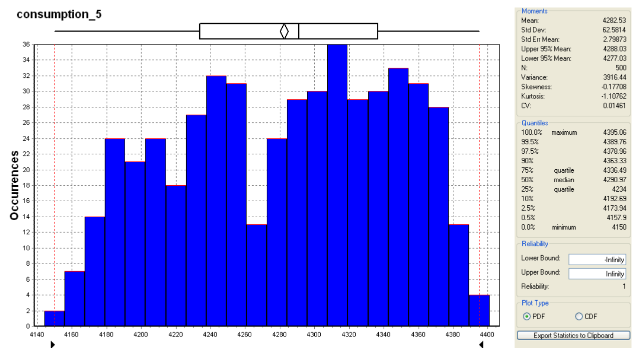

Figure C.120; Healthcare System 4; Energy Consumption @ 5 years average; Mean 0.75

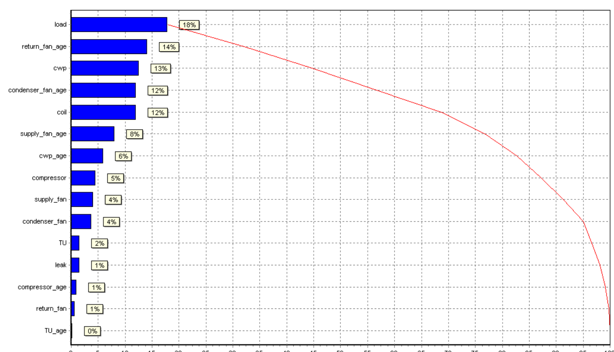

Figure C.121; Healthcare System 4; Sensitivity analysis results; Mean 0.75

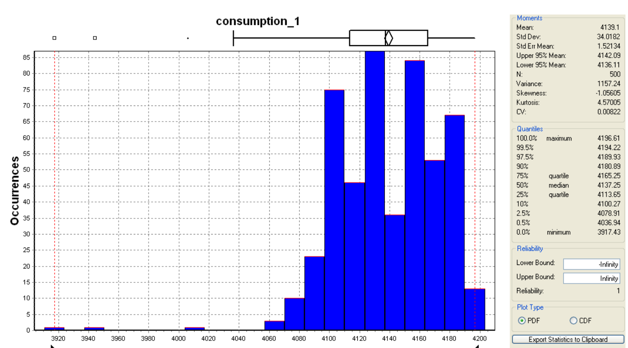

Figure C.122; Healthcare System 4; Energy Consumption @ first year; Mean 0.5

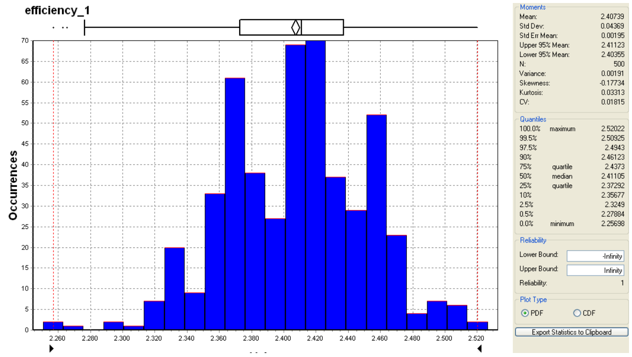

Figure C.123; Healthcare System 4; Energy Efficiency @ first year; Mean 0.5

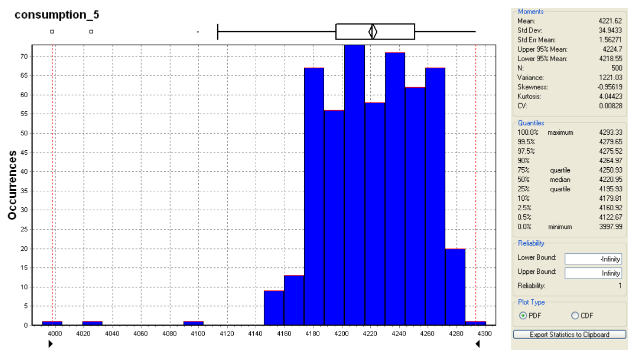

Figure C.124; Healthcare System 4; Energy Consumption @ 5 years average; Mean 0.5

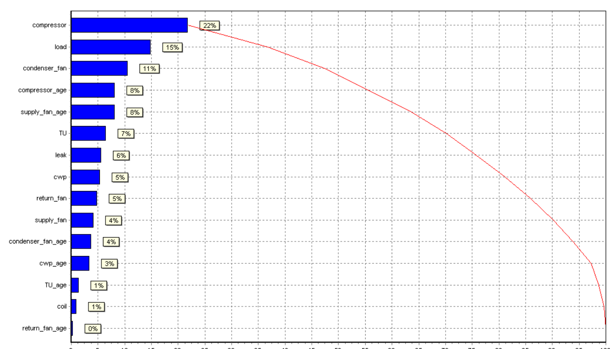

Figure C.125; Healthcare System 4; Sensitivity analysis results; Mean 0.5

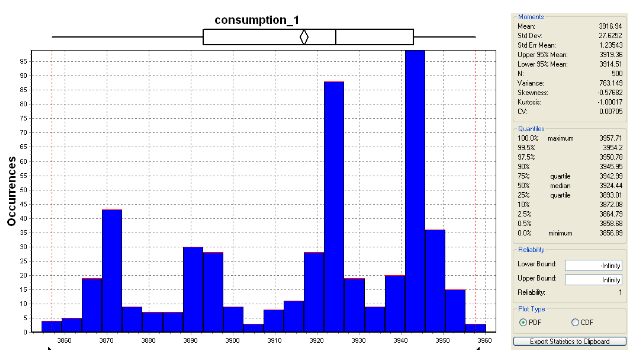

Figure C.126; Healthcare System 4; Energy Consumption @ first year; Mean 0.25

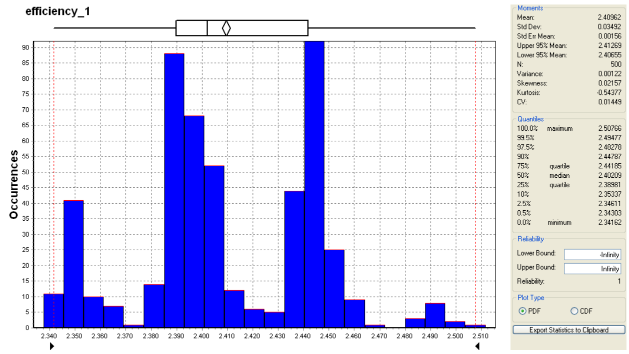


Figure C.127; Healthcare System 4; Energy Efficiency @ first year; Mean 0.25

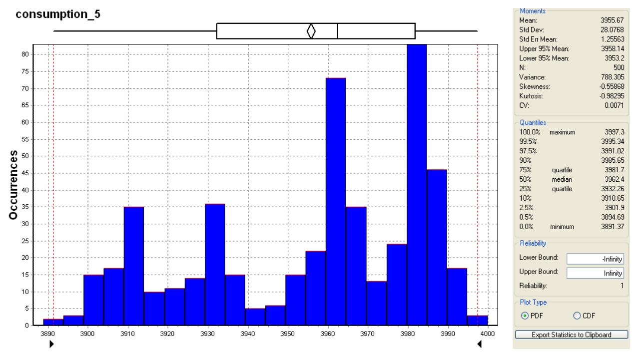


Figure C.128; Healthcare System 4; Energy Consumption @ 5 years average; Mean 0.25

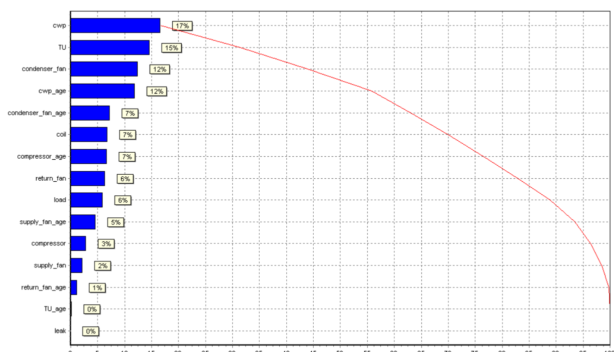


Figure C.129; Healthcare System 4; Sensitivity analyzing results; Mean 0.25

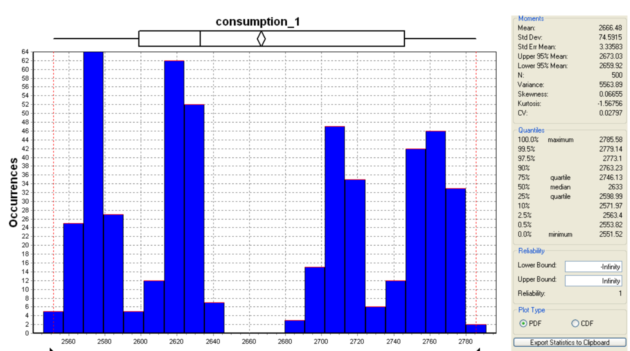


Figure C.130; Healthcare System 5; Energy Consumption @ first year; Mean 0.75

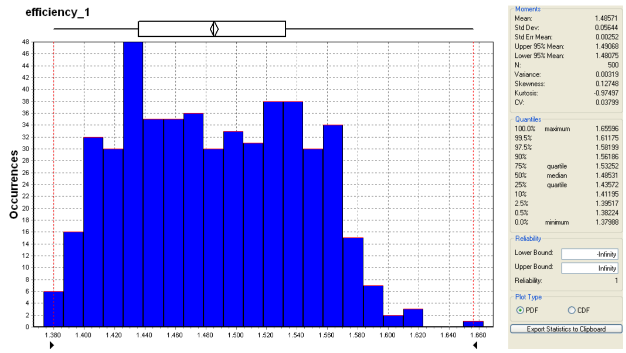

Figure C.131; Healthcare System 5; Energy Efficiency @ first year; Mean 0.75

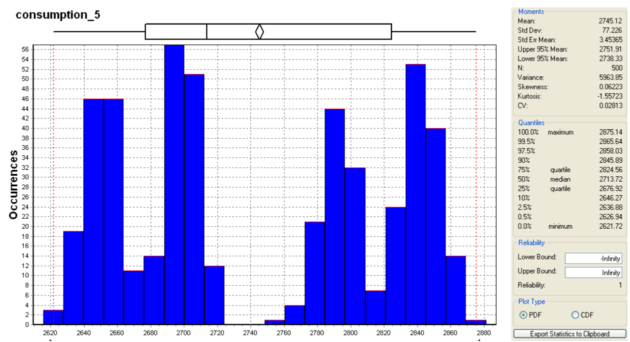

Figure C.132; Healthcare System 5; Energy Consumption @ 5 years average; Mean 0.75

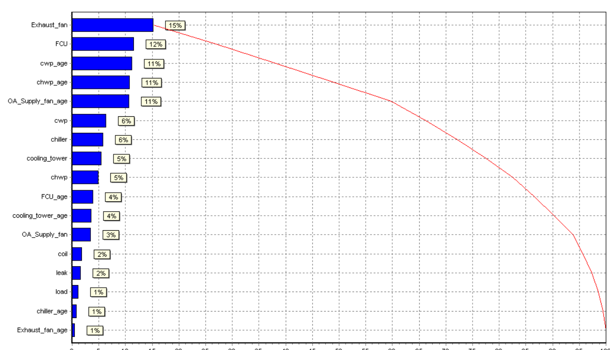

Figure C.133; Healthcare System 5; Sensitivity analysis results; Mean 0.75

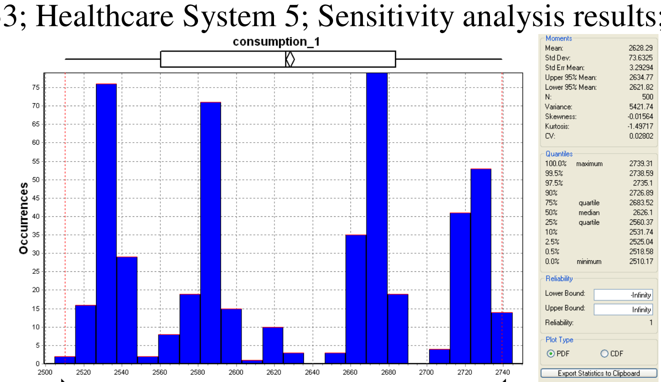

Figure C.134; Healthcare System 5; Energy Consumption @ first year; Mean 0.5

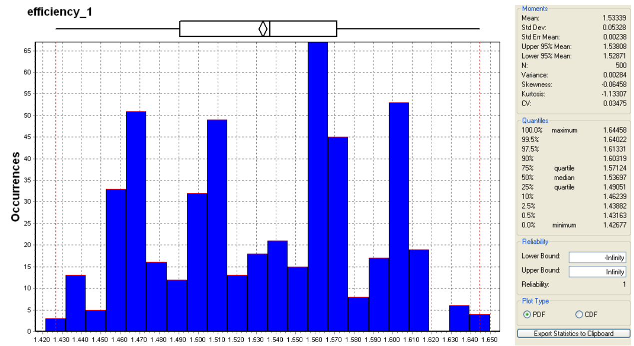

Figure C.135; Healthcare System 5; Energy Efficiency @ first year; Mean 0.5

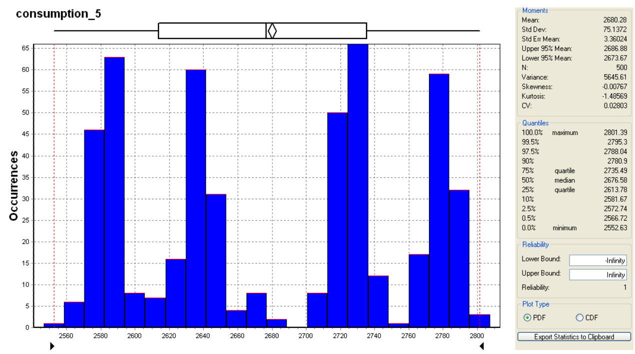

Figure C.136; Healthcare System 5; Energy Consumption @ 5 years average; Mean 0.5

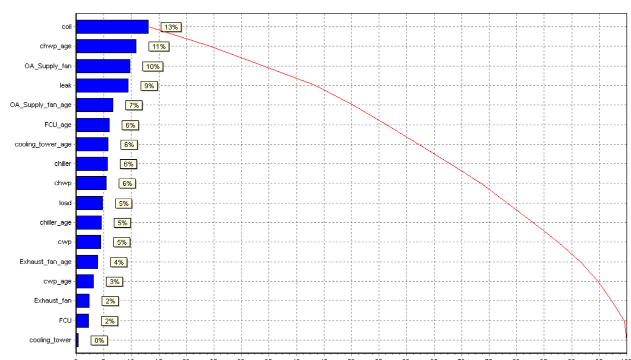

Figure C.137; Healthcare System 5; Sensitivity analysis results; Mean 0.5

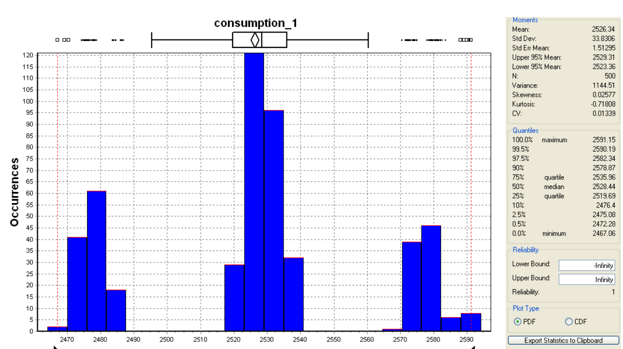

Figure C.138; Healthcare System 5; Energy Consumption @ first year; Mean 0.25

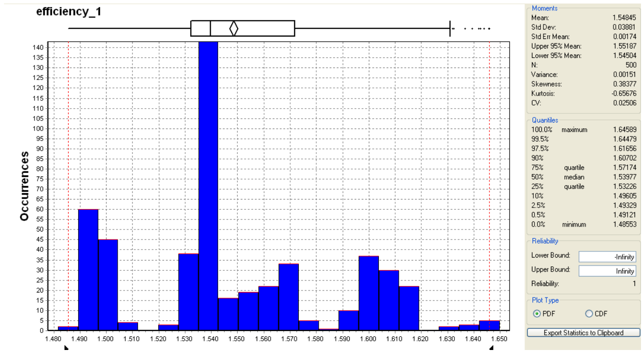

Figure C.139; Healthcare System 5; Energy Efficiency @ first year; Mean 0.25

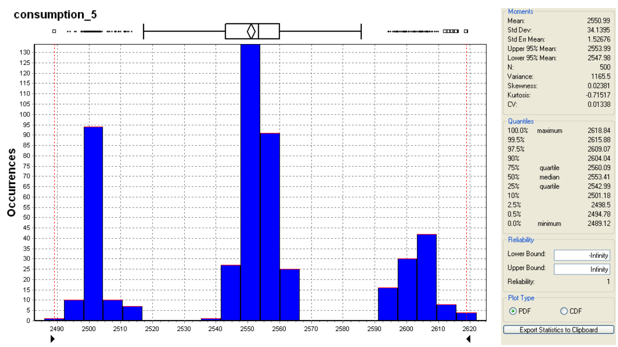

Figure C.140; Healthcare System 5; Energy Consumption @ 5 years average; Mean 0.25

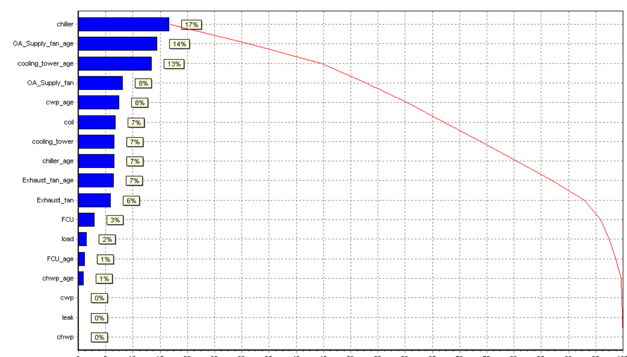

Figure C.141; Healthcare System 5; Sensitivity analysis results; Mean 0.25

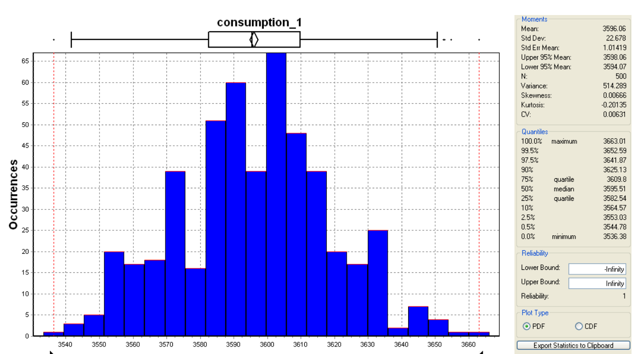

Figure C.142; Healthcare System 6; Energy Consumption @ first year; Mean 0.75

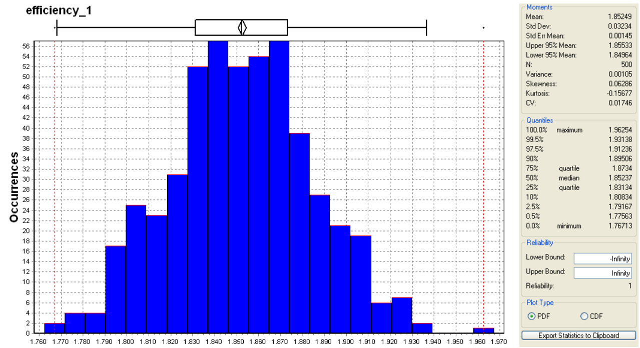

Figure C.143; Healthcare System 6; Energy Efficiency @ first year; Mean 0.75

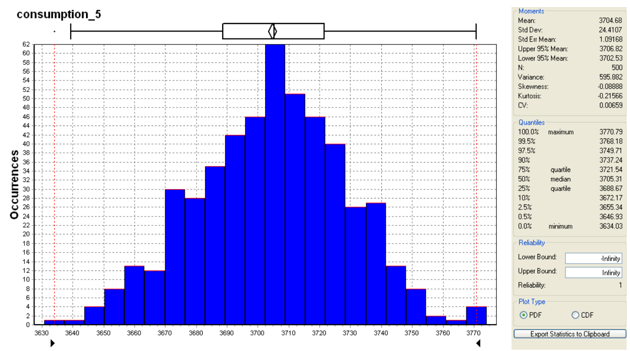

Figure C.144; Healthcare System 6; Energy Consumption @ 5 years average; Mean 0.75

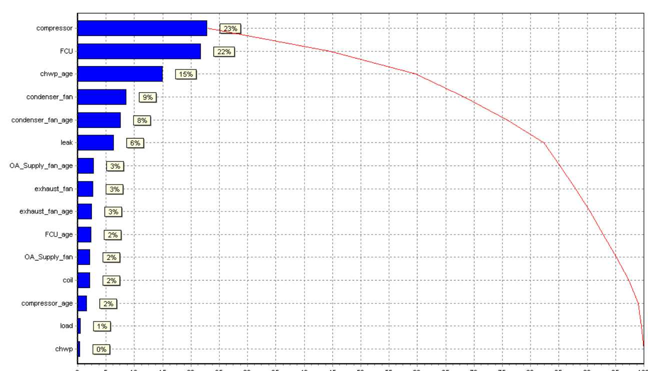

Figure C.145; Healthcare System 6; Sensitivity analysis results @ first year; Mean 0.75

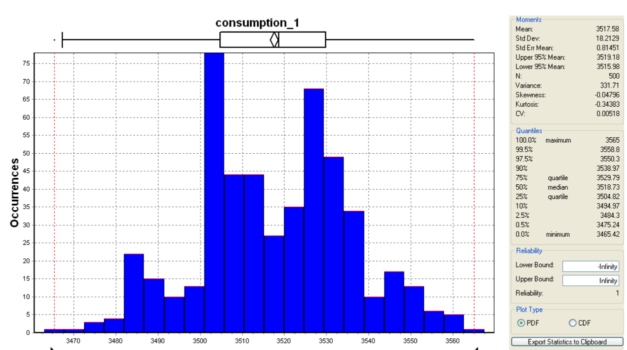

Figure C.146; Healthcare System 6; Energy Consumption @ first year; Mean 0.5

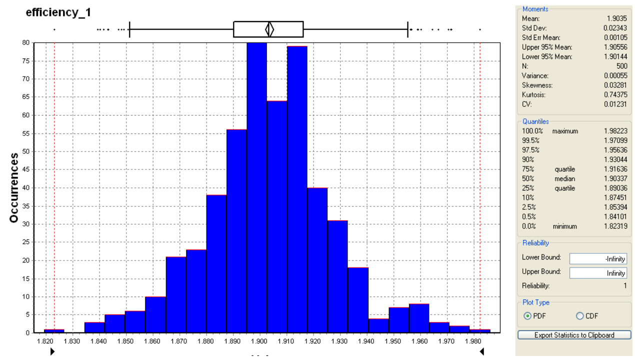

Figure C.147; Healthcare System 6; Energy Efficiency @ first year; Mean 0.5

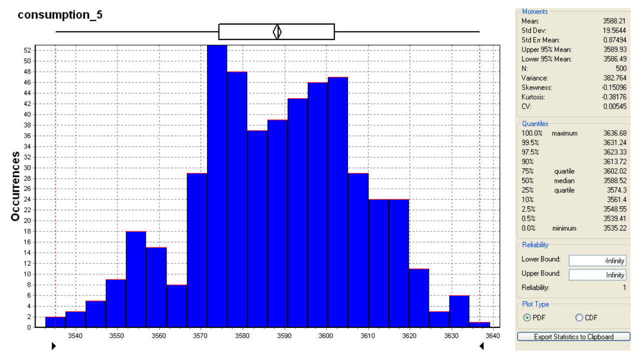

Figure C.148; Healthcare System 6; Energy Consumption @ 5 years average; Mean 0.5

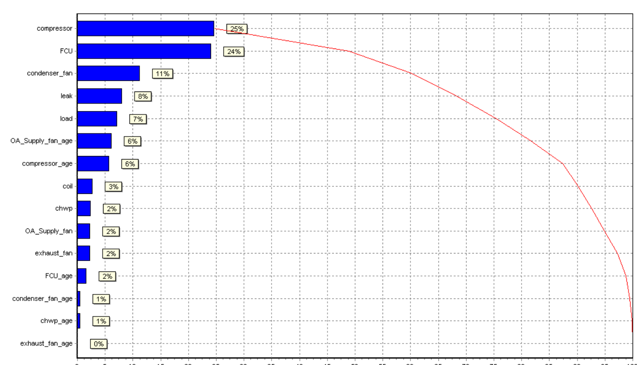

Figure C.149; Healthcare System 6; Sensitivity analysis results; Mean 0.5

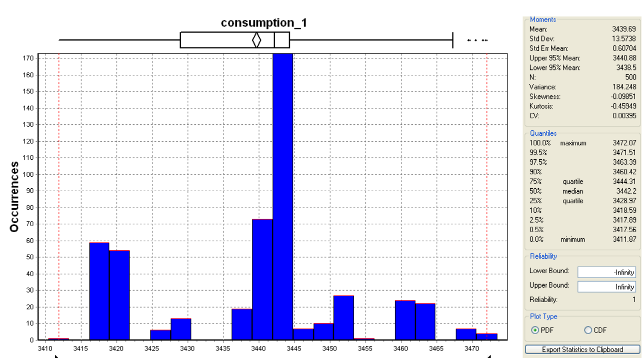

Figure C.150; Healthcare System 6; Energy Consumption @ first year; Mean 0.25

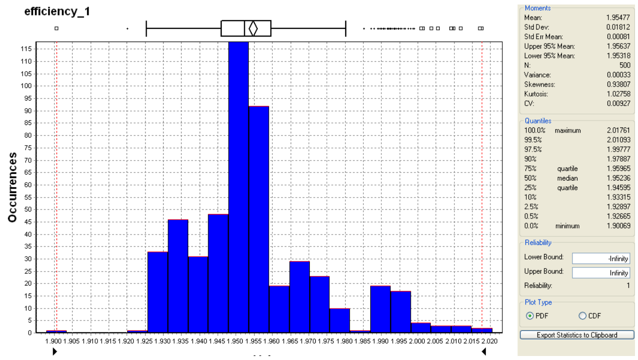

Figure C.151; Healthcare System 6; Energy Efficiency @ first year; Mean 0.25

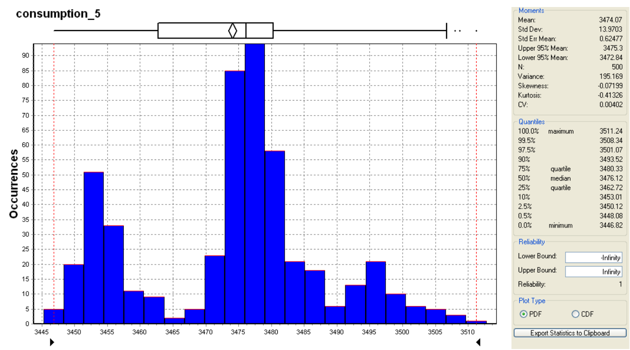

Figure C.152; Healthcare System 6; Energy Consumption @ 5 years average; Mean 0.25

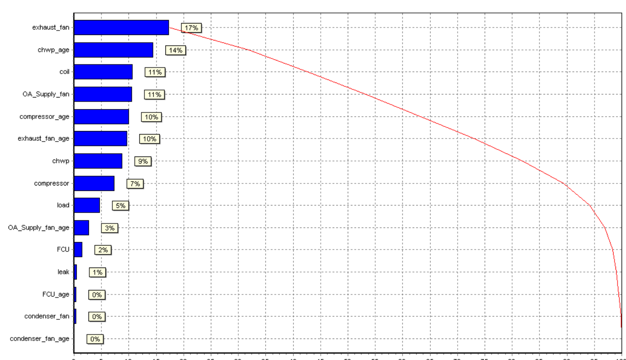

Figure C.153; Healthcare System 6; Sensitivity analysis results; Mean 0.25

# APPENDIX D

# SENSOR ACCURACY UNCERTAINTY

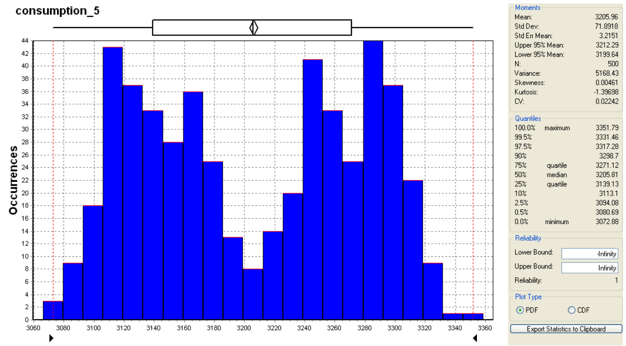

Figure D.1; Office System 1; Sensors with +-5% Accuracy, 5 years average, Mean 0.75

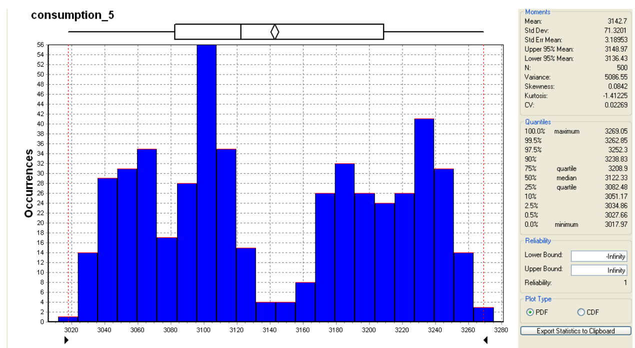

Figure D.2; Office System 1; Sensors with +-5% Accuracy, 5 years average, Mean 0.5

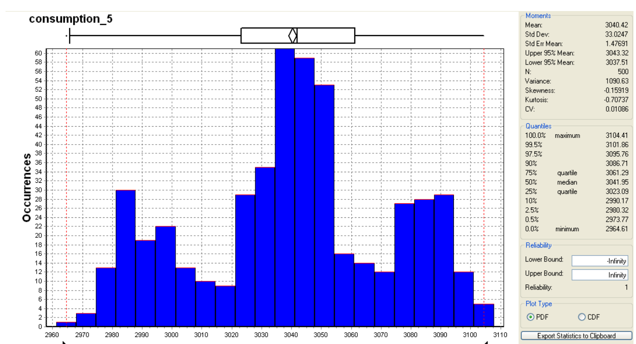

Figure D.3; Office System 1; Sensors with +-5% Accuracy, 5 years average, Mean 0.25

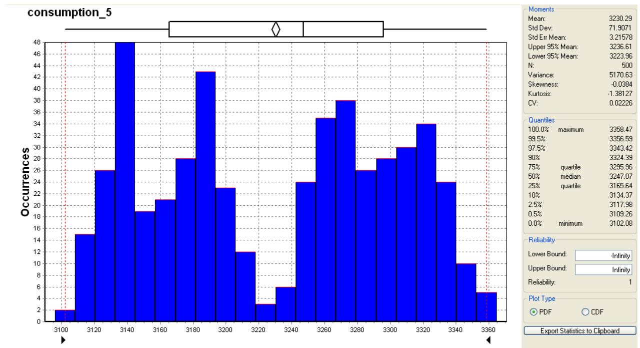


Figure D.4; Office System 1; Sensors with +-2% Accuracy, 5 years average, Mean 0.75

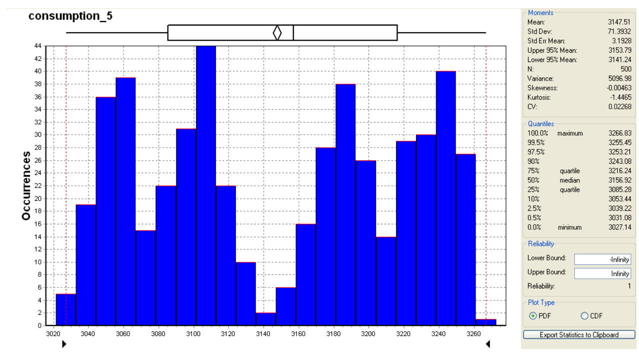


Figure D.5; Office System 1; Sensors with +-2% Accuracy, 5 years average, Mean 0.5

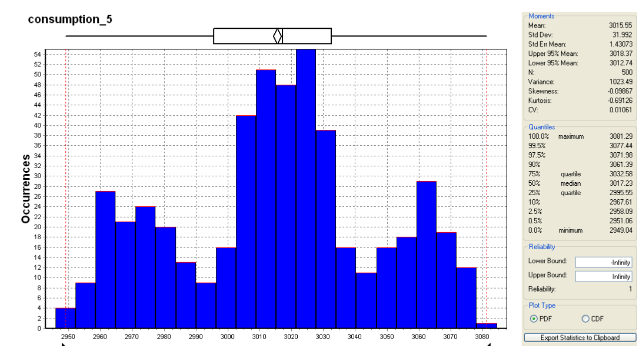


Figure D.6; Office System 1; Sensors with +-2% Accuracy, 5 years average, Mean 0.25

# APPENDIX E

# DETERMINISTIC VERSUS PROBABILISTIC COMPARISON

# (HEALTHCARE)

Table E.1: System 1 (Healthcare) energy consumption comparison deterministic vs. probabilistic

| Deterministic kwh | Probabilistic kwh | % Difference | Bin Size | % Probability | % Cumulative |
|---|---|---|---|---|---|
| 3016 | | | | | |
| | 2980 | -1.19 | 0.1 | 0.1 | 0.01 |
| | 2990 | -0.86 | 1.2 | 0.08 | 0.09 |
| | 3000 | -0.53 | 3.8 | 0.25 | 0.34 |
| | 3010 | -0.20 | 0.4 | 0.03 | 0.37 |
| | 3020 | 0.13 | 4.8 | 0.32 | 32.97 |
| | 3030 | 0.46 | 0.2 | 0.01 | 32.65 |
| | 3040 | 0.80 | 8.7 | 0.58 | 32.63 |
| | 3050 | 1.13 | 6 | 0.4 | 32.05 |
| | 3060 | 1.46 | 15.9 | 1.06 | 31.65 |
| | 3070 | 1.79 | 10.3 | 0.69 | 30.59 |
| | 3080 | 2.12 | 7 | 0.47 | 29.91 |
| | 3090 | 2.45 | 3.1 | 0.21 | 29.44 |
| | 3100 | 2.79 | 19.1 | 1.27 | 29.23 |
| | 3110 | 3.12 | 0.4 | 0.03 | 27.96 |
| | 3120 | 3.45 | 30.3 | 2.02 | 27.93 |
| | 3130 | 3.78 | 0.8 | 0.05 | 25.91 |
| | 3140 | 4.11 | 54 | 3.6 | 25.86 |
| | 3150 | 4.44 | 0 | 0 | 22.26 |
| | 3160 | 4.77 | 31.5 | 2.1 | 22.26 |
| | 3170 | 5.11 | 0 | 0 | 20.16 |
| | 3180 | 5.44 | 17.7 | 1.18 | 20.16 |
| | 3190 | 5.77 | 0 | 0 | 18.98 |
| | 3200 | 6.10 | 48.6 | 3.24 | 18.98 |
| | 3210 | 6.43 | 0 | 0 | 15.74 |
| | 3220 | 6.76 | 30 | 2 | 15.74 |
| | 3230 | 7.10 | 0 | 0 | 13.74 |
| | 3240 | 7.43 | 17.1 | 1.14 | 13.74 |
| | 3250 | 7.76 | 0 | 0 | 12.6 |
| | 3260 | 8.09 | 48 | 3.2 | 12.6 |
| | 3270 | 8.42 | 0 | 0 | 9.4 |
| | 3280 | 8.75 | 35.4 | 2.36 | 9.4 |
| | 3290 | 9.08 | 0 | 0 | 7.04 |

Table E.1 continued

| | | | | | |
|---|---|---|---|---|---|
| | 3300 | 9.42 | 38.4 | 2.56 | 7.04 |
| | 3310 | 9.75 | 0 | 0 | 4.48 |
| | 3320 | 10.08 | 19.2 | 1.28 | 4.48 |
| | 3330 | 10.41 | 0 | 0 | 3.2 |
| | 3340 | 10.74 | 34.2 | 2.28 | 3.2 |
| | 3350 | 11.07 | 0 | 0 | 0.92 |
| | 3360 | 11.41 | 13.8 | 0.92 | 0.92 |
| | | | 500 | | |

Table E.2: System 1 sensitivity analysis results Healthcare (relevance of component)

| Equipment_1 | 75% bin | 50% bin | 25% bin | Average |
|---|---|---|---|---|
| Chiller_ age | 8 | 6 | 14 | 9.33 |
| CWP_ age | 4 | 8 | 15 | 9.00 |
| Chiller | 12 | 4 | 9 | 8.33 |
| RF_ age | 8 | 12 | 3 | 7.67 |
| Leak | 7 | 6 | 10 | 7.67 |
| Load | 3 | 11 | 7 | 7.00 |
| Cooling_ Tower | 2 | 9 | 10 | 7.00 |
| Coil | 8 | 7 | 5 | 6.67 |
| Cooling_ Tower_ age | 10 | 4 | 4 | 6.00 |
| Terminal Unit | 7 | 11 | 0 | 6.00 |
| Terminal Unit_ age | 10 | 5 | 2 | 5.67 |
| Supply_ Fan | 3 | 5 | 8 | 5.33 |
| CHWP | 2 | 4 | 5 | 3.67 |
| Return_ Fan | 7 | 3 | 0 | 3.33 |
| CWP | 5 | 0 | 3 | 2.67 |
| CHWP_ age | 2 | 2 | 3 | 2.33 |
| Supply_ Fan_ age | 3 | 2 | 1 | 2.00 |

Table E.3: System 2 (Healthcare) energy consumption comparison deterministic vs. probabilistic

| Deterministic kwh | Probabilistic kwh | % Difference | Bin Size | % Probability | % Cumulative |
|---|---|---|---|---|---|
| 3912 | | | | | |
| | 3930 | 0.46 | 3.2 | 0.64 | 100 |
| | 3940 | 0.72 | 2.3 | 0.46 | 99.36 |
| | 3950 | 0.97 | 3 | 0.6 | 98.9 |
| | 3960 | 1.23 | 12.8 | 2.56 | 98.3 |
| | 3970 | 1.48 | 8 | 1.6 | 95.74 |
| | 3980 | 1.74 | 11.5 | 2.3 | 94.14 |
| | 3990 | 1.99 | 6.5 | 1.3 | 91.84 |
| | 4000 | 2.25 | 1.8 | 0.36 | 90.54 |
| | 4010 | 2.51 | 3.3 | 0.66 | 90.18 |
| | 4020 | 2.76 | 6 | 1.2 | 89.52 |
| | 4030 | 3.02 | 9.9 | 1.98 | 88.32 |
| | 4040 | 3.27 | 19.2 | 3.84 | 86.34 |
| | 4050 | 3.53 | 20.7 | 4.14 | 82.5 |
| | 4060 | 3.78 | 27 | 5.4 | 78.36 |
| | 4070 | 4.04 | 25.8 | 5.16 | 72.96 |
| | 4080 | 4.29 | 12.9 | 2.58 | 67.8 |
| | 4090 | 4.55 | 17.1 | 3.42 | 65.22 |
| | 4100 | 4.81 | 6.3 | 1.26 | 61.8 |
| | 4110 | 5.06 | 5.7 | 1.14 | 60.54 |
| | 4120 | 5.32 | 9.6 | 1.92 | 59.4 |
| | 4130 | 5.57 | 10.8 | 2.16 | 57.48 |
| | 4140 | 5.83 | 40.8 | 8.16 | 55.32 |
| | 4150 | 6.08 | 27 | 5.4 | 47.16 |
| | 4160 | 6.34 | 59.4 | 11.88 | 41.76 |
| | 4170 | 6.60 | 27 | 5.4 | 29.88 |
| | 4180 | 6.85 | 53.4 | 10.68 | 24.48 |
| | 4190 | 7.11 | 24 | 4.8 | 13.8 |
| | 4200 | 7.36 | 28.2 | 5.64 | 9 |
| | 4210 | 7.62 | 13.2 | 2.64 | 3.36 |
| | 4220 | 7.87 | 2.4 | 0.48 | 0.72 |
| | 4230 | 8.13 | 1.2 | 0.24 | 0.24 |
| | | | 500 | | |

Table E.4: System 2 sensitivity analysis results Healthcare (relevance of component)

| Equipment_2 | 75% bin | 50% bin | 25% bin | Average |
|---|---|---|---|---|
| Compressor_ age | 14 | 15 | 6 | 11.67 |
| Supply_ Fan | 5 | 18 | 10 | 11.00 |
| Terminal Unit | 13 | 3 | 10 | 8.67 |
| CHWP_ age | 12 | 5 | 8 | 8.33 |
| Compressor | 12 | 4 | 9 | 8.33 |
| RF_ age | 11 | 2 | 12 | 8.33 |
| Condenser_ fan | 7 | 13 | 5 | 8.33 |
| Load | 7 | 7 | 10 | 8.00 |
| Terminal Unit_ age | 7 | 2 | 9 | 6.00 |
| Coil | 1 | 10 | 2 | 4.33 |
| Leak | 4 | 7 | 1 | 4.00 |
| Supply_ Fan_ age | 3 | 7 | 2 | 4.00 |
| Condenser_ fan_ age | 7 | 0 | 2 | 3.00 |
| Return_ Fan | 1 | 5 | 3 | 3.00 |
| CHWP | 3 | 0 | 4 | 2.33 |

Table E.5: System 3 (Healthcare) energy consumption comparison deterministic vs. probabilistic

| Deterministic kwh | Probabilistic kwh | % Difference | Bin Size | % Probability | % Cumulative |
|---|---|---|---|---|---|
| 4169 | | | | | |
| | 3100 | -25.64 | 6 | 1.2 | 1.2 |
| | 4160 | -0.22 | 0.3 | 0.06 | 1.26 |
| | 4170 | 0.02 | 2.4 | 0.48 | 98.74 |
| | 4180 | 0.26 | 3.6 | 0.72 | 98.26 |
| | 4190 | 0.50 | 15.5 | 3.1 | 97.54 |
| | 4200 | 0.74 | 7 | 1.4 | 94.44 |
| | 4210 | 0.98 | 8.5 | 1.7 | 93.04 |
| | 4220 | 1.22 | 9.8 | 1.96 | 91.34 |
| | 4230 | 1.46 | 2.6 | 0.52 | 89.38 |
| | 4240 | 1.70 | 0.3 | 0.06 | 88.86 |
| | 4250 | 1.94 | 0.6 | 0.12 | 88.8 |
| | 4260 | 2.18 | 0.6 | 0.12 | 88.68 |
| | 4270 | 2.42 | 10.8 | 2.16 | 88.56 |
| | 4280 | 2.66 | 11.1 | 2.22 | 86.4 |
| | 4290 | 2.90 | 18 | 3.6 | 84.18 |
| | 4300 | 3.14 | 21.6 | 4.32 | 80.58 |
| | 4310 | 3.38 | 27.9 | 5.58 | 76.26 |
| | 4320 | 3.62 | 24 | 4.8 | 70.68 |
| | 4330 | 3.86 | 12.6 | 2.52 | 65.88 |
| | 4340 | 4.10 | 12.6 | 2.52 | 63.36 |
| | 4350 | 4.34 | 5.4 | 1.08 | 60.84 |
| | 4360 | 4.58 | 4.8 | 0.96 | 59.76 |
| | 4370 | 4.82 | 4.5 | 0.9 | 58.8 |
| | 4380 | 5.06 | 0.9 | 0.18 | 57.9 |
| | 4390 | 5.30 | 0.6 | 0.12 | 57.72 |
| | 4400 | 5.54 | 228 | 45.6 | 57.6 |
| | 4500 | 7.94 | 60 | 12 | 12 |
| | | | 500 | | |

Table E.6: System 3 sensitivity analysis results Healthcare (relevance of component)

| Equipment_3 | 75% bin | 50% bin | 25% bin | Average |
|---|---|---|---|---|
| Compressor | 44 | 24 | 3 | 23.67 |
| Coil | 44 | 4 | 3 | 17.00 |
| Compressor_ age | 1 | 10 | 17 | 9.33 |
| Terminal Unit_ age | 1 | 4 | 20 | 8.33 |
| Supply_ Fan | 1 | 10 | 12 | 7.67 |
| Condenser_ fan | 1 | 11 | 8 | 6.67 |
| Condenser_ fan_ age | 1 | 15 | 1 | 5.67 |
| Load | 2 | 4 | 9 | 5.00 |
| Return_ Fan | 1 | 2 | 9 | 4.00 |
| Terminal Unit | 1 | 4 | 6 | 3.67 |
| RF_ age | 1 | 1 | 9 | 3.67 |
| Supply_ Fan_ age | 1 | 7 | 1 | 3.00 |
| Leak | 1 | 4 | 2 | 2.33 |

Table E.7: System 4 (Healthcare) energy consumption comparison deterministic vs. probabilistic

| Deterministic kwh | Probabilistic kwh | % Difference | Bin Size | % Probability | % Cumulative |
|---|---|---|---|---|---|
| 3881 | | | | | |
| | 3860 | -0.54 | 0.9 | 0.18 | 0.18 |
| | 3870 | -0.28 | 6.5 | 1.3 | 1.48 |
| | 3880 | -0.03 | 1.6 | 0.32 | 1.8 |
| | 3890 | 0.23 | 3.7 | 0.74 | 98.2 |
| | 3900 | 0.49 | 3.9 | 0.78 | 97.46 |
| | 3910 | 0.75 | 1.1 | 0.22 | 96.68 |
| | 3920 | 1.00 | 4.3 | 0.86 | 96.46 |
| | 3930 | 1.26 | 8.8 | 1.76 | 95.6 |
| | 3940 | 1.52 | 4.5 | 0.9 | 93.84 |
| | 3950 | 1.78 | 13.5 | 2.7 | 92.94 |
| | 3960 | 2.04 | 1.8 | 0.36 | 90.24 |
| | 3970 | 2.29 | 0 | 0 | 89.88 |
| | 3980 | 2.55 | 0 | 0 | 89.88 |
| | 3990 | 2.81 | 0 | 0 | 89.88 |
| | 4000 | 3.07 | 0 | 0 | 89.88 |
| | 4010 | 3.32 | 0 | 0 | 89.88 |
| | 4020 | 3.58 | 0.3 | 0.06 | 89.88 |
| | 4030 | 3.84 | 0 | 0 | 89.82 |
| | 4040 | 4.10 | 11.4 | 2.28 | 89.82 |
| | 4050 | 4.35 | 0 | 0 | 87.54 |
| | 4060 | 4.61 | 24 | 4.8 | 87.54 |
| | 4070 | 4.87 | 0 | 0 | 82.74 |
| | 4080 | 5.13 | 36.3 | 7.26 | 82.74 |
| | 4090 | 5.39 | 0 | 0 | 75.48 |
| | 4100 | 5.64 | 32.7 | 6.54 | 75.48 |
| | 4110 | 5.90 | 0 | 0 | 68.94 |
| | 4120 | 6.16 | 78.9 | 15.78 | 68.94 |
| | 4130 | 6.42 | 0 | 0 | 53.16 |
| | 4140 | 6.67 | 31.5 | 6.3 | 53.16 |
| | 4150 | 6.93 | 0 | 0 | 46.86 |
| | 4160 | 7.19 | 57 | 11.4 | 46.86 |
| | 4170 | 7.45 | 0 | 0 | 35.46 |

Table E.7 continued

| | | | | | |
|---|---|---|---|---|---|
| | 4180 | 7.70 | 75 | 15 | 35.46 |
| | 4190 | 7.96 | 0 | 0 | 20.46 |
| | 4200 | 8.22 | 39.9 | 7.98 | 20.46 |
| | 4210 | 8.48 | 0 | 0 | 12.48 |
| | 4220 | 8.73 | 33.6 | 6.72 | 12.48 |
| | 4230 | 8.99 | 0 | 0 | 5.76 |
| | 4240 | 9.25 | 27.6 | 5.52 | 5.76 |
| | 4250 | 9.51 | 0 | 0 | 0.24 |
| | 4260 | 9.77 | 1.2 | 0.24 | 0.24 |
| | | | 500 | | |

Table E.8: System 4 sensitivity analysis results Healthcare (relevance of component)

| Equipment_4 | 75% bin | 50% bin | 25% bin | Average |
|---|---|---|---|---|
| Compressor | 4 | 23 | 8 | 11.67 |
| Condenser_ fan | 13 | 4 | 12 | 9.67 |
| Load | 21 | 3 | 1 | 8.33 |
| Return_ Fan | 11 | 8 | 6 | 8.33 |
| Supply_ Fan | 10 | 8 | 7 | 8.33 |
| CWP_ age | 9 | 2 | 9 | 6.67 |
| RF_ age | 6 | 1 | 13 | 6.67 |
| Compressor_ age | 2 | 9 | 7 | 6.00 |
| CWP | 4 | 14 | 0 | 6.00 |
| Leak | 4 | 0 | 14 | 6.00 |
| Supply_ Fan_ age | 3 | 3 | 8 | 4.67 |
| Condenser_ fan_ age | 1 | 4 | 8 | 4.33 |
| Terminal Unit_ age | 3 | 5 | 4 | 4.00 |
| Coil | 3 | 8 | 1 | 4.00 |
| Terminal Unit | 6 | 6 | 0 | 4.00 |

Table E.9: System 5 (Healthcare) energy consumption comparison deterministic vs. probabilistic

| Deterministic kwh | Probabilistic kwh | % Difference | Bin Size | % Probability | % Cumulative |
|---|---|---|---|---|---|
| 2564 | | | | | |
| | 2470 | -3.67 | 0.2 | 0.04 | 0.04 |
| | 2480 | -3.28 | 10.2 | 2.04 | 2.08 |
| | 2490 | -2.89 | 1.7 | 0.34 | 2.42 |
| | 2500 | -2.50 | 0 | 0 | 2.42 |
| | 2510 | -2.11 | 0 | 0 | 2.42 |
| | 2520 | -1.72 | 8 | 1.6 | 4.02 |
| | 2530 | -1.33 | 22.1 | 4.42 | 8.44 |
| | 2540 | -0.94 | 34.9 | 6.98 | 15.42 |
| | 2550 | -0.55 | 0 | 0 | 15.42 |
| | 2560 | -0.16 | 21 | 4.2 | 19.62 |
| | 2570 | 0.23 | 4 | 0.8 | 80.38 |
| | 2580 | 0.62 | 86.2 | 17.24 | 79.58 |
| | 2590 | 1.01 | 1.2 | 0.24 | 62.34 |
| | 2600 | 1.40 | 15 | 3 | 62.1 |
| | 2610 | 1.79 | 0 | 0 | 59.1 |
| | 2620 | 2.18 | 41.1 | 8.22 | 59.1 |
| | 2630 | 2.57 | 0 | 0 | 50.88 |
| | 2640 | 2.96 | 35.4 | 7.08 | 50.88 |
| | 2650 | 3.35 | 0 | 0 | 43.8 |
| | 2660 | 3.74 | 11.4 | 2.28 | 43.8 |
| | 2670 | 4.13 | 0 | 0 | 41.52 |
| | 2680 | 4.52 | 31.5 | 6.3 | 41.52 |
| | 2690 | 4.91 | 0 | 0 | 35.22 |
| | 2700 | 5.30 | 10.2 | 2.04 | 35.22 |
| | 2710 | 5.69 | 0 | 0 | 33.18 |
| | 2720 | 6.08 | 60.6 | 12.12 | 33.18 |
| | 2730 | 6.47 | 0 | 0 | 21.06 |
| | 2740 | 6.86 | 30.9 | 6.18 | 21.06 |
| | 2750 | 7.25 | 0 | 0 | 14.88 |
| | 2760 | 7.64 | 52.8 | 10.56 | 14.88 |
| | 2770 | 8.03 | 0 | 0 | 4.32 |
| | 2780 | 8.42 | 21.6 | 4.32 | 4.32 |
| | | | 500 | | |

Table E.10: System 5 sensitivity analysis results Healthcare (relevance of component)

| Equipment_5 | 75% bin | 50% bin | 25% bin | Average |
|---|---|---|---|---|
| Supply_ Fan_ age | 11 | 7 | 14 | 10.67 |
| Chiller | 6 | 6 | 17 | 9.67 |
| Return_ Fan | 15 | 2 | 6 | 7.67 |
| CHWP_ age | 11 | 11 | 1 | 7.67 |
| Cooling_ Tower_ age | 4 | 6 | 13 | 7.67 |
| Coil | 2 | 13 | 7 | 7.33 |
| CWP_ age | 11 | 3 | 8 | 7.33 |
| Supply_ Fan | 3 | 10 | 8 | 7.00 |
| FCU | 12 | 2 | 3 | 5.67 |
| Chiller_ age | 1 | 5 | 7 | 4.33 |
| RF_ age | 1 | 4 | 7 | 4.00 |
| Cooling_ Tower | 5 | 0 | 7 | 4.00 |
| FCU_ age | 4 | 6 | 1 | 3.67 |
| Leak | 2 | 9 | 0 | 3.67 |
| CHWP | 5 | 6 | 0 | 3.67 |
| CWP | 6 | 5 | 0 | 3.67 |
| Load | 1 | 5 | 2 | 2.67 |

Table E.11: System 6 (Healthcare) energy consumption comparison deterministic vs. probabilistic

| Deterministic kwh | Probabilistic kwh | % Difference | Bin Size | % Probability | % Cumulative |
|---|---|---|---|---|---|
| 3503 | | | | | |
| | 3410 | -2.65 | 0.1 | 0.02 | 0.02 |
| | 3420 | -2.37 | 11.8 | 2.36 | 2.38 |
| | 3430 | -2.08 | 1.2 | 0.24 | 2.62 |
| | 3440 | -1.80 | 25.2 | 5.04 | 7.66 |
| | 3450 | -1.51 | 4.7 | 0.94 | 8.6 |
| | 3460 | -1.23 | 5.1 | 1.02 | 9.62 |
| | 3470 | -0.94 | 2.5 | 0.5 | 10.12 |
| | 3480 | -0.66 | 2.1 | 0.42 | 10.54 |
| | 3490 | -0.37 | 7.5 | 1.5 | 12.04 |
| | 3500 | -0.09 | 30.3 | 6.06 | 18.1 |
| | 3510 | 0.20 | 29.4 | 5.88 | 81.9 |
| | 3520 | 0.49 | 21 | 4.2 | 76.02 |
| | 3530 | 0.77 | 35.1 | 7.02 | 71.82 |
| | 3540 | 1.06 | 15.6 | 3.12 | 64.8 |
| | 3550 | 1.34 | 12 | 2.4 | 61.68 |
| | 3560 | 1.63 | 24 | 4.8 | 59.28 |
| | 3570 | 1.91 | 34.2 | 6.84 | 54.48 |
| | 3580 | 2.20 | 9.6 | 1.92 | 47.64 |
| | 3590 | 2.48 | 66.6 | 13.32 | 45.72 |
| | 3600 | 2.77 | 63.6 | 12.72 | 32.4 |
| | 3610 | 3.05 | 28.8 | 5.76 | 19.68 |
| | 3620 | 3.34 | 35.4 | 7.08 | 13.92 |
| | 3630 | 3.63 | 25.2 | 5.04 | 6.84 |
| | 3640 | 3.91 | 1.8 | 0.36 | 1.8 |
| | 3650 | 4.20 | 7.2 | 1.44 | 1.44 |
| | | | **500** | | |

Table E.12: System 6 sensitivity analysis results Healthcare (relevance of component)

| Equipment_6 | 75% bin | 50% bin | 25% bin | Average |
|---|---|---|---|---|
| Compressor | 23 | 25 | 7 | 18.33 |
| FCU | 22 | 24 | 2 | 16.00 |
| CHWP_ age | 15 | 1 | 14 | 10.00 |
| Return_ Fan | 3 | 2 | 17 | 7.33 |
| Condenser_ fan | 9 | 11 | 0 | 6.67 |
| Compressor_ age | 2 | 6 | 10 | 6.00 |
| Coil | 2 | 3 | 11 | 5.33 |
| Supply_ Fan | 2 | 2 | 11 | 5.00 |
| Leak | 6 | 8 | 1 | 5.00 |
| RF_ age | 3 | 0 | 10 | 4.33 |
| Load | 1 | 7 | 5 | 4.33 |
| Supply_ Fan_ age | 3 | 6 | 3 | 4.00 |
| CHWP | 0 | 2 | 9 | 3.67 |
| Condenser_ fan_ age | 8 | 1 | 0 | 3.00 |
| FCU_ age | 2 | 2 | 0 | 1.33 |

# APPENDIX F

# ENERGY CONSUMPTION UNCERTAINTY FOR SYSTEMS WITH LARGER CAPACITY

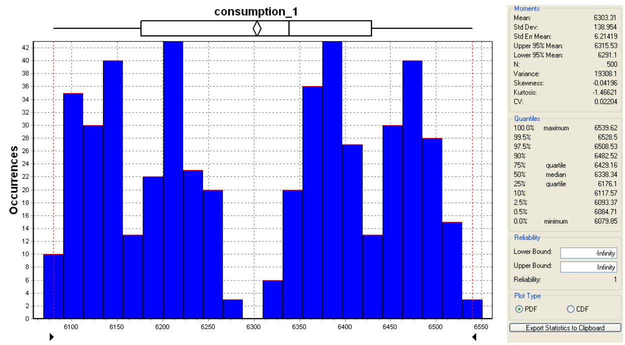


Figure F.1; Office System 1A (Capacity: system 1 x 2); Energy Consumption, 1$^{st}$ year, Mean 0.75

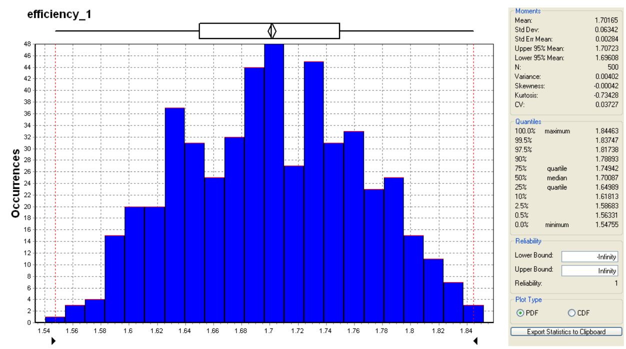


Figure F.2; Office System 1A (Capacity: system 1 x 2); Efficiency, 1$^{st}$ year, Mean 0.75

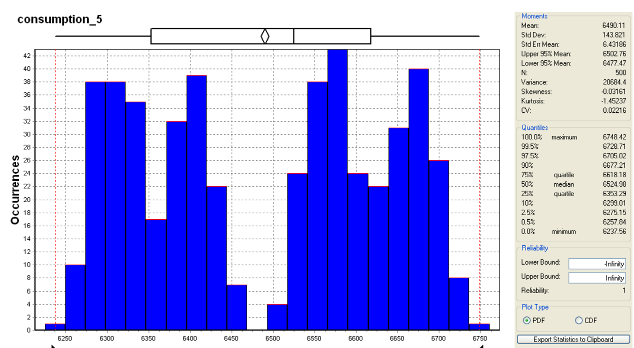


Figure F.3; Office System 1A (Capacity: system 1 x 2); Energy Consumption, 5 years average, Mean 0.75

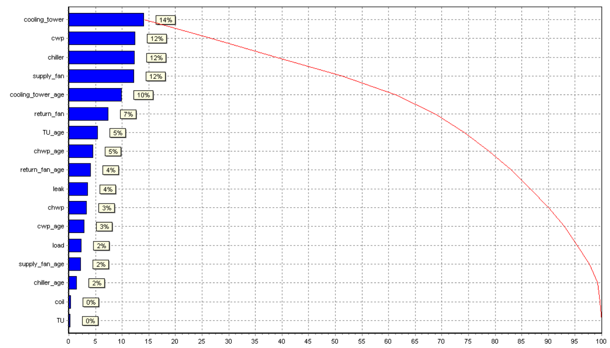


Figure F.4; Office System 1A (Capacity: system 1 x 2); Sensitivity analysis results, Mean 0.75

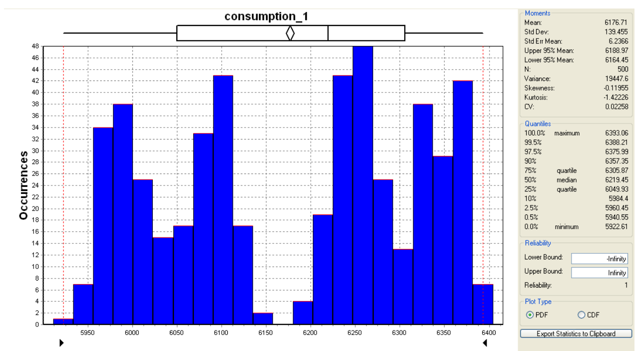


Figure F.5; Office System 1A (Capacity: system 1 x 2); Energy Consumption, 1st year, Mean 0.5

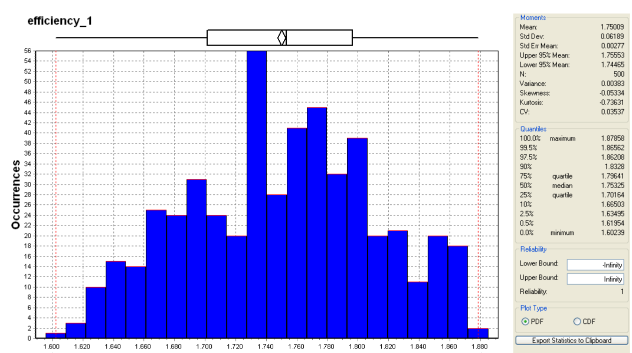


Figure F.6; Office System 1A (Capacity: system 1 x 2); Efficiency, 1st year, Mean 0.5

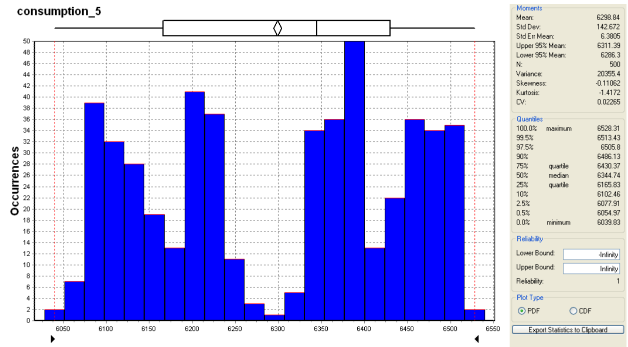


Figure F.7; Office System 1A (Capacity: system 1 x 2); Energy Consumption, 5 years average, Mean 0.5

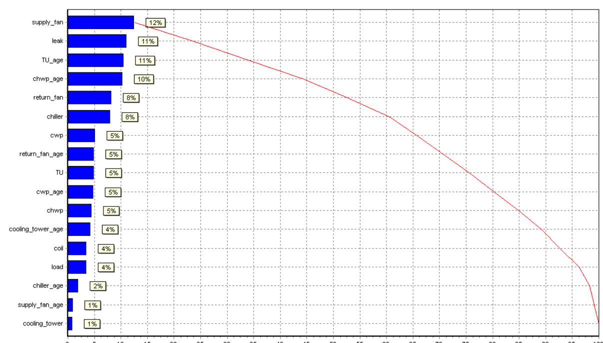

Figure F.8; Office System 1A (Capacity: system 1 x 2); Sensitivity analysis results, Mean 0.5

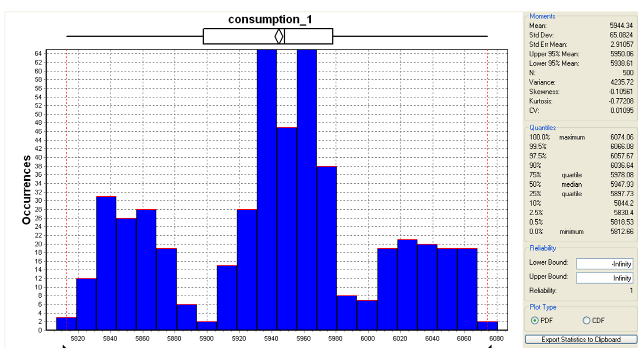


Figure F.9; Office System 1A (Capacity: system 1 x 2); Energy Consumption, 1st year, Mean 0.25

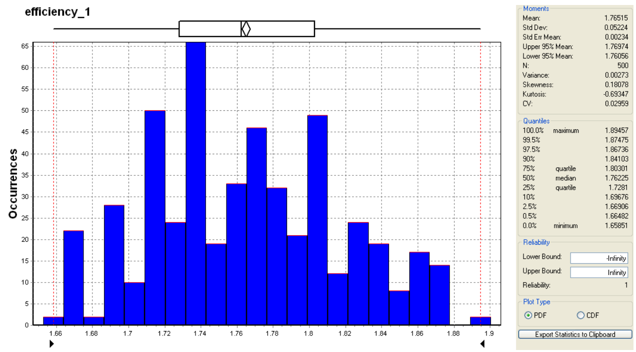


Figure F.10; Office System 1A (Capacity: system 1 x 2); Efficiency, 1st year, Mean 0.25

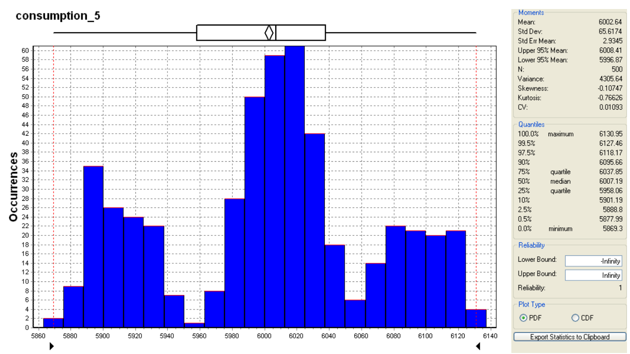


Figure F.11; Office System 1A (Capacity: system 1 x 2); Energy Consumption, 5 years average, Mean 0.25

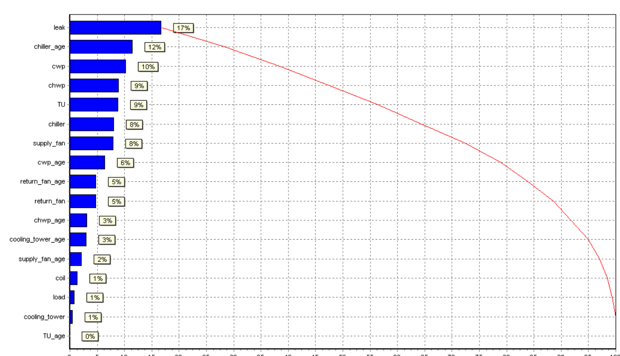


Figure F.12; Office System 1A (Capacity: system 1 x 2); Sensitivity analysis results, Mean 0.25

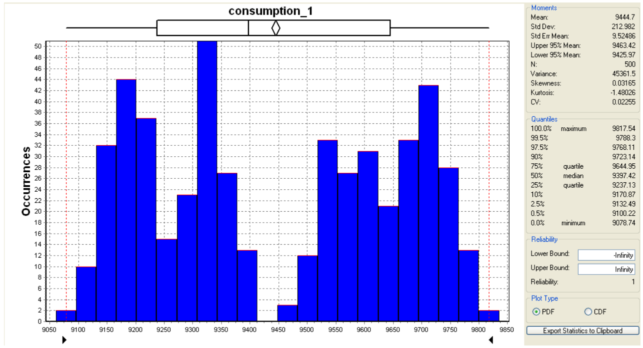


Figure F.13; Office System 1B (Capacity: system 1 x 3); Energy Consumption, 1st year, Mean 0.75

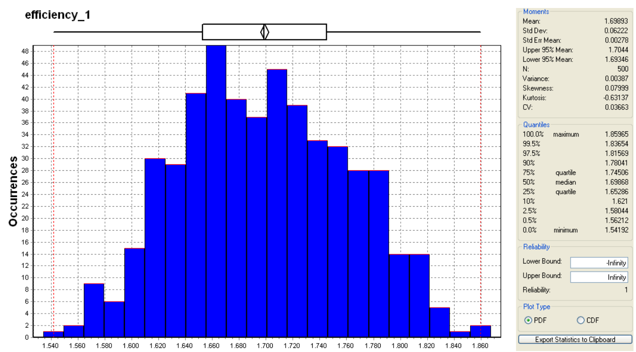


Figure F.14; Office System 1B (Capacity: system 1 x 3); Efficiency, 1st year, Mean 0.75

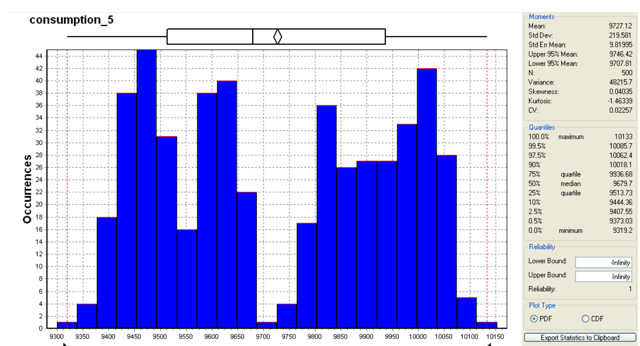


Figure F.15; Office System 1B (Capacity: system 1 x 3); Energy Consumption, 5 years average, Mean 0.75

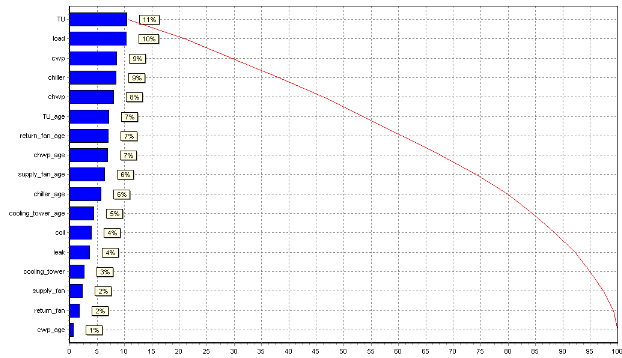


Figure F.16; Office System 1B (Capacity: system 1 x 3); Sensitivity analysis results, Mean 0.75

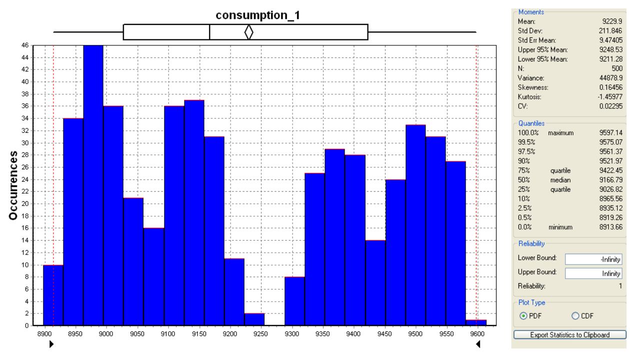


Figure F.17; Office System 1B (Capacity: system 1 x 3); Energy Consumption, 1st year, Mean 0.5

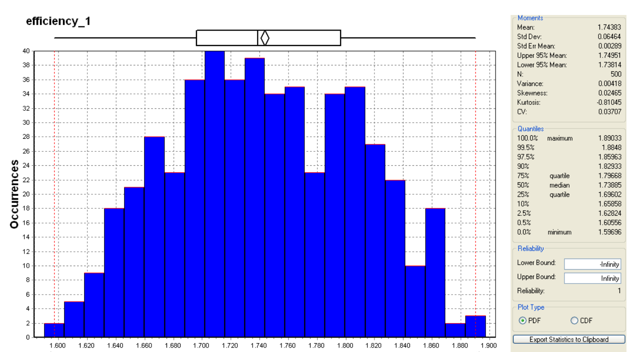


Figure F.18; Office System 1B (Capacity: system 1 x 3); Efficiency, 1st year, Mean 0.5

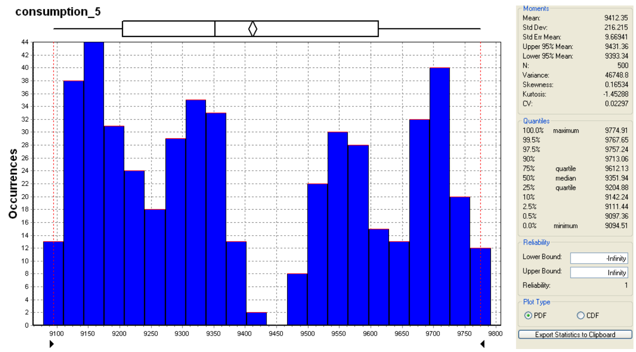


Figure F.19; Office System 1B (Capacity: system 1 x 3); Energy Consumption, 5 years average, Mean 0.5

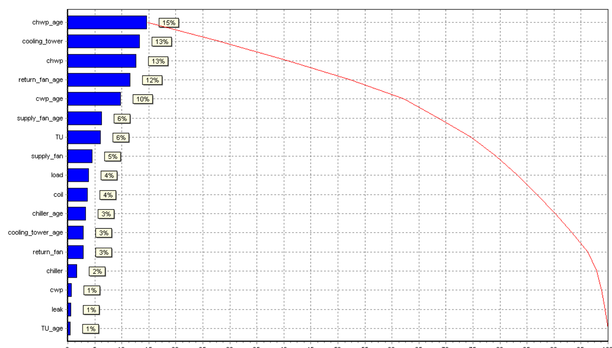


Figure F.20; Office System 1B (Capacity: system 1 x 3); Sensitivity analysis results, Mean 0.5

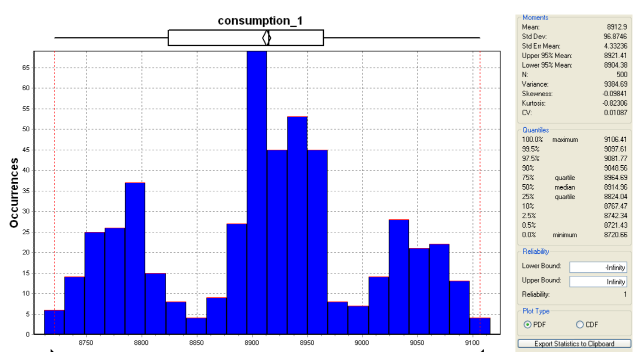


Figure F.21; Office System 1B (Capacity: system 1 x 3); Energy Consumption, 1st year, Mean 0.25

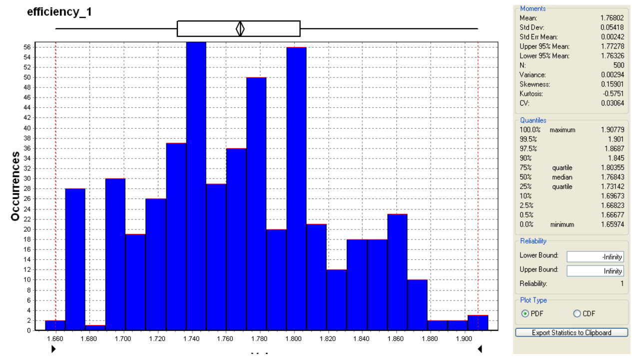


Figure F.22; Office System 1B (Capacity: system 1 x 3); Efficiency, 1st year, Mean 0.25

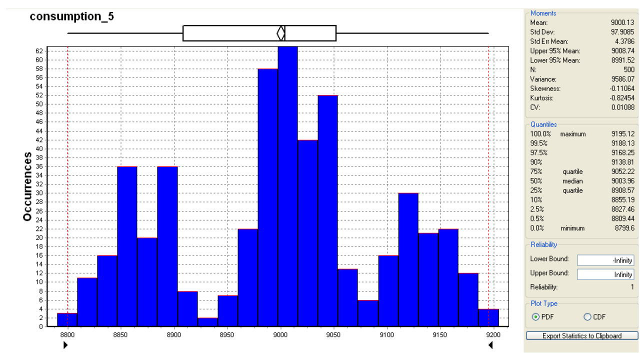


Figure F.23; Office System 1B (Capacity: system 1 x 3); Energy Consumption, 5 years average, Mean 0.25

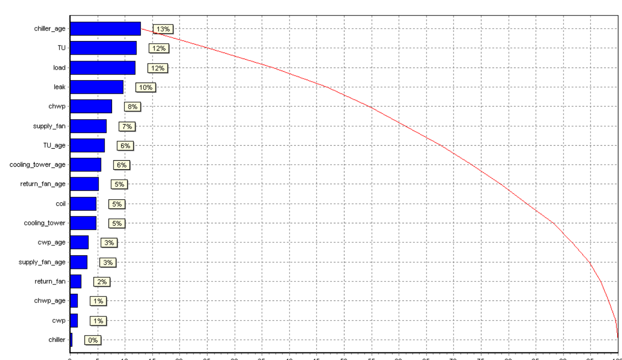


Figure F.24; Office System 1B (Capacity: system 1 x 3); Sensitivity analysis results, Mean 0.25

Table F.1; Office Systems 1, 1A, 1B; Component influence

| | System 1 | System 1A | System 1B |
|---|---|---|---|
| Chiller | 8.07 | 9.60 | 3.03 |
| Chiller age | 10.44 | 2.30 | 3.69 |
| Supply Fan | 3.68 | 12.06 | 4.49 |
| Supply Fan age | 2.18 | 1.21 | 5.82 |
| Return Fan | 1.25 | 8.69 | 2.76 |
| Return Fan age | 5.75 | 5.79 | 10.81 |
| Cooling Tower | 5.42 | 3.15 | 10.97 |
| Cooling Tower age | 2.51 | 5.02 | 3.35 |
| Chilled Water Pump | 8.39 | 5.02 | 11.85 |
| Chilled Water Pump age | 8.50 | 9.13 | 13.09 |
| Condenser Water Pump | 3.13 | 6.36 | 2.26 |
| Condenser Water Pump age | 6.95 | 4.77 | 8.21 |
| Terminal Unit | 3.41 | 4.36 | 6.85 |
| Terminal Unit age | 5.37 | 5.40 | 2.07 |
| Leak | 10.65 | 10.17 | 1.70 |
| Load | 3.95 | 3.65 | 5.10 |
| Coil | 10.35 | 3.32 | 3.96 |

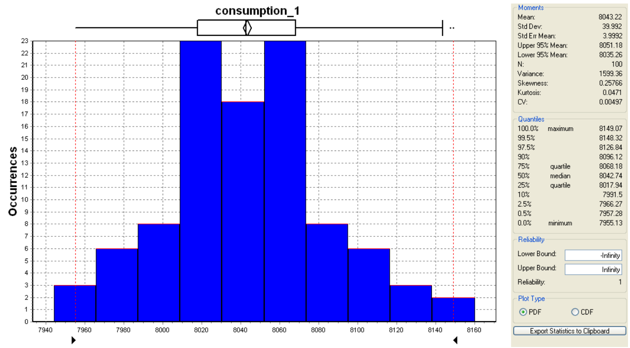


Figure F.25; Office System 2A (Capacity: system 2 x 2); Energy Consumption, 1st year, Mean 0.75

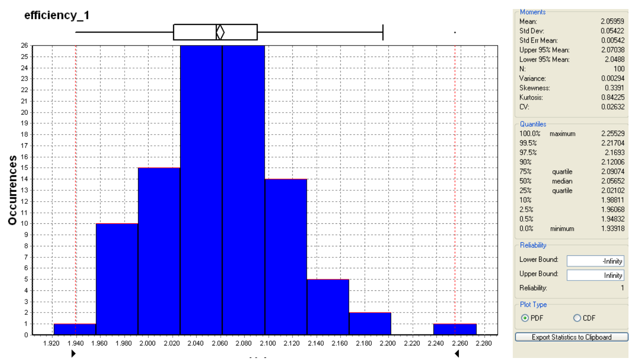


Figure F.26; Office System 2A (Capacity: system 2 x 2); Efficiency, 1st year, Mean 0.75

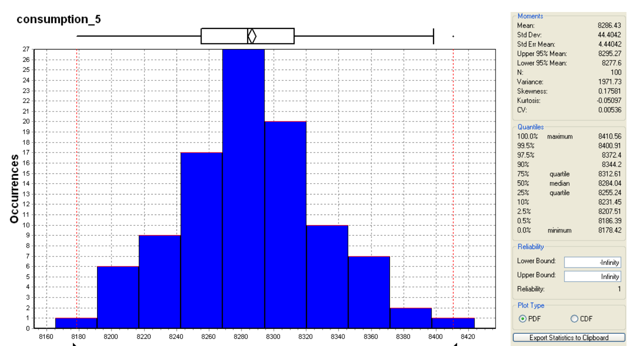


Figure F.27; Office System 2A (Capacity: system 2 x 2); Energy Consumption, 5 years average, Mean 0.75

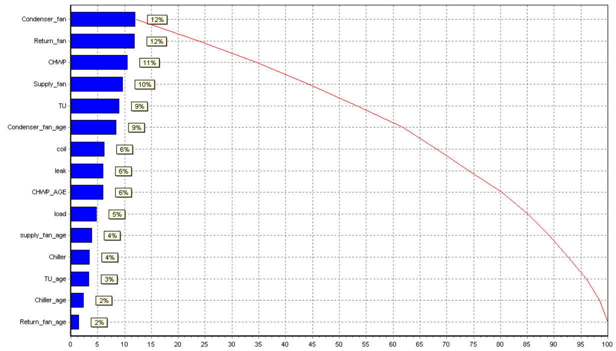


Figure F.28; Office System 2A (Capacity: system 2 x 2); Sensitivity analysis results, Mean 0.75

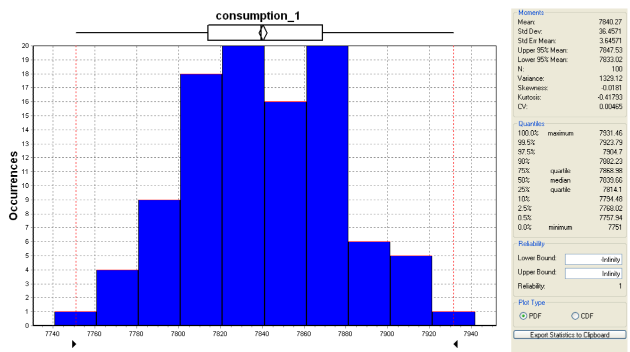


Figure F.29; Office System 2A (Capacity: system 2 x 2); Energy Consumption, 1$^{st}$ year, Mean 0.5

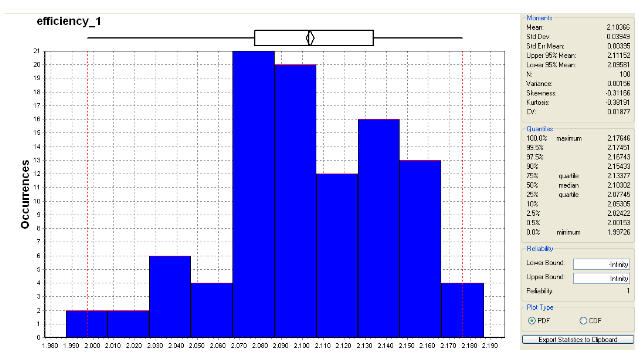


Figure F.30; Office System 2A (Capacity: system 2 x 2); Efficiency, 1$^{st}$ year, Mean 0.5

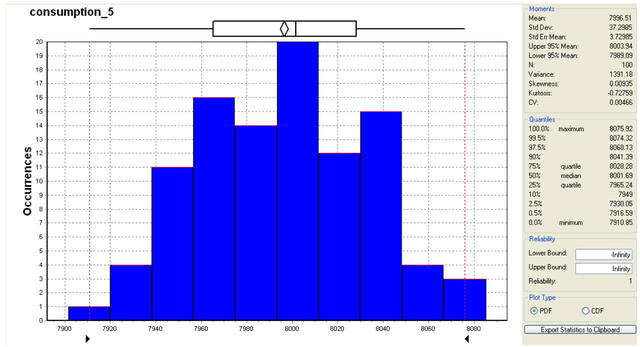


Figure F.31; Office System 2A (Capacity: system 2 x 2); Energy Consumption, 5 years average, Mean 0.5

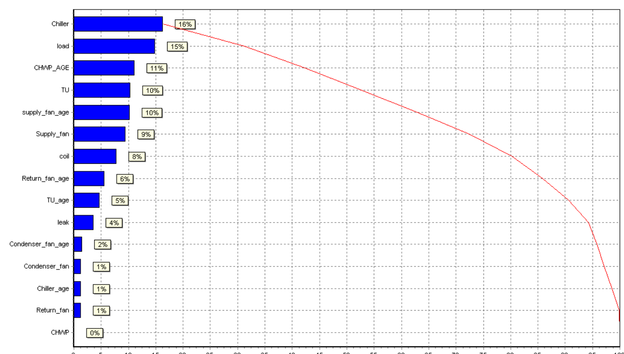

Figure F.32; Office System 2A (Capacity: system 2 x 2); Sensitivity analysis results, Mean 0.5

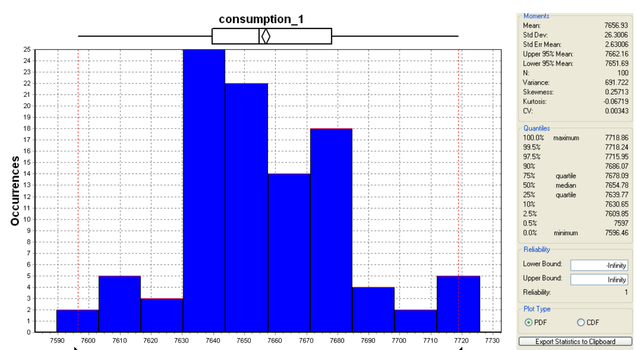


Figure F.33; Office System 2A (Capacity: system 2 x 2); Energy Consumption, 1st year, Mean 0.25

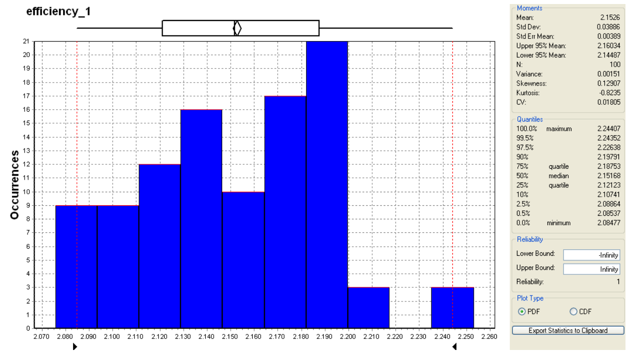

Figure F.34; Office System 2A (Capacity: system 2 x 2); Efficiency, 1st year, Mean 0.25

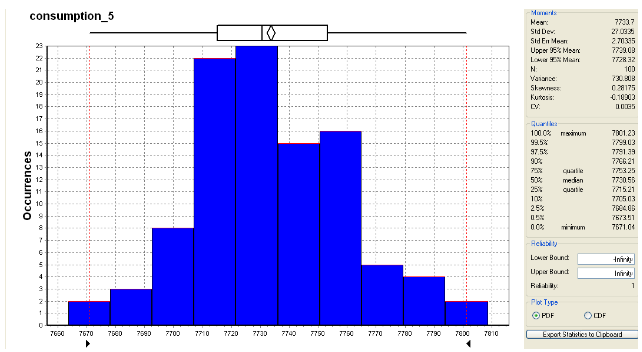

Figure F.35; Office System 2A (Capacity: system 2 x 2); Energy Consumption, 5 years average, Mean 0.25

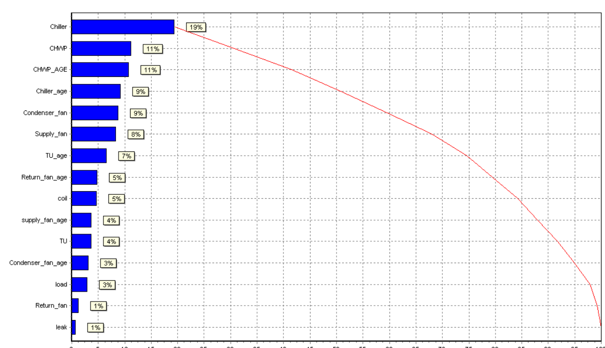

Figure F.36; Office System 2A (Capacity: system 2 x 2); Sensitivity analysis results, Mean 0.25

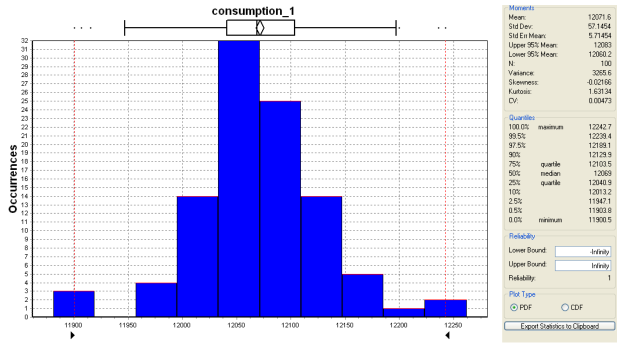


Figure F.37; Office System 2B (Capacity: system 2 x 3); Energy Consumption, 1st year, Mean 0.75

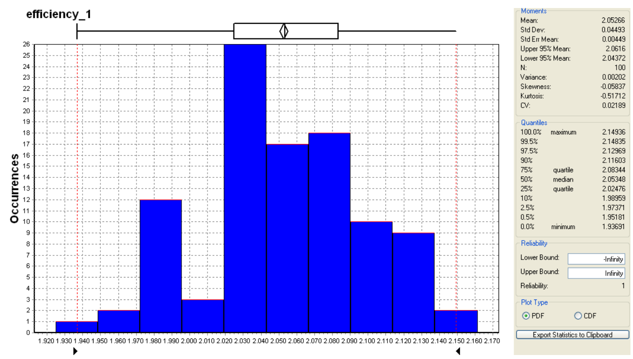


Figure F.38; Office System 2B (Capacity: system 2 x 3); Efficiency, 1st year, Mean 0.75

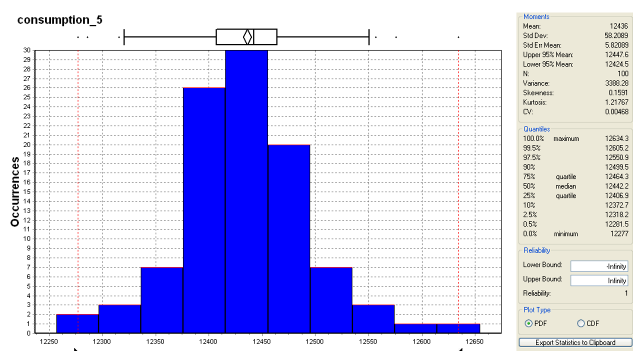


Figure F.39; Office System 2B (Capacity: system 2 x 3); Energy Consumption, 5 years average, Mean 0.75

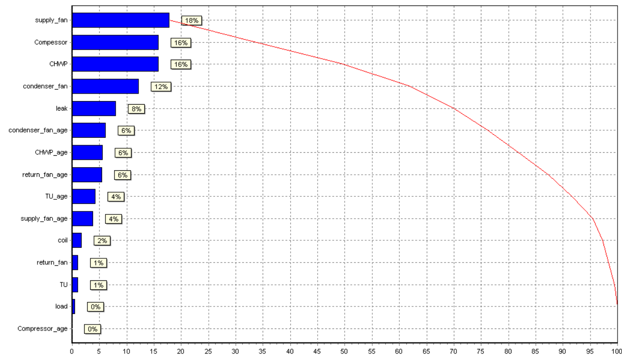


Figure F.40; Office System 2B (Capacity: system 2 x 3); Sensitivity analysis results, Mean 0.75

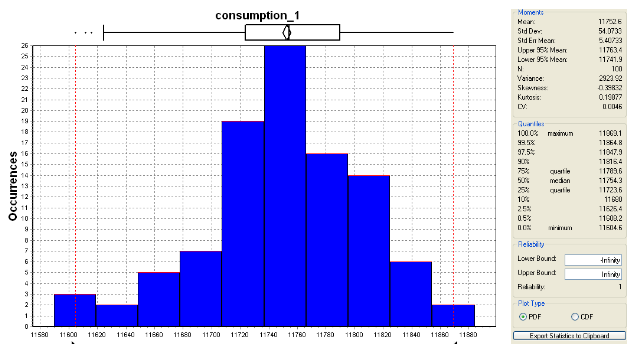


Figure F.41; Office System 2B (Capacity: system 2 x 3); Energy Consumption, 1st year, Mean 0.5

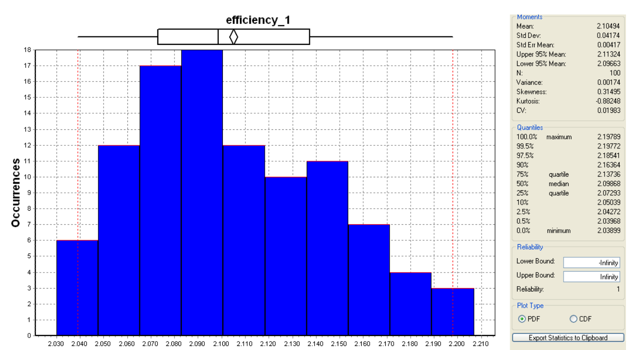


Figure F.42; Office System 2B (Capacity: system 2 x 3); Efficiency, 1st year, Mean 0.5

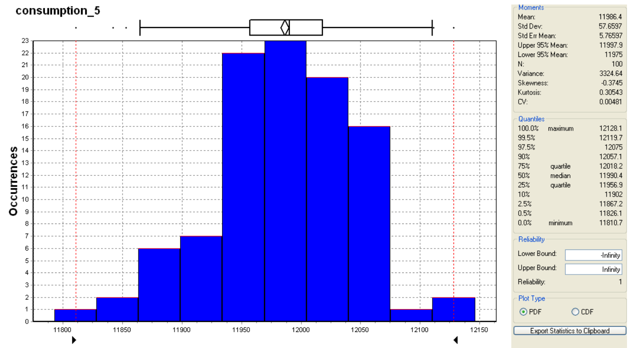


Figure F.43; Office System 2B (Capacity: system 2 x 3); Energy Consumption, 5 years average, Mean 0.5

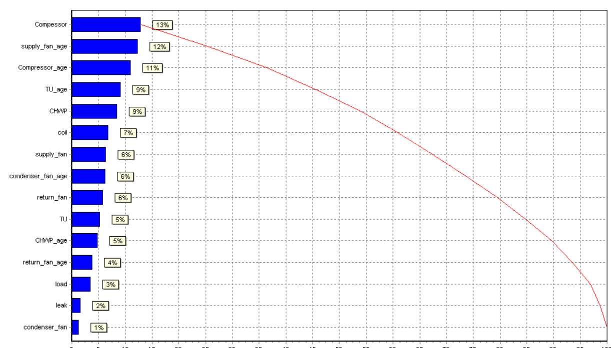


Figure F.44; Office System 2B (Capacity: system 2 x 3); Sensitivity analysis results, Mean 0.5

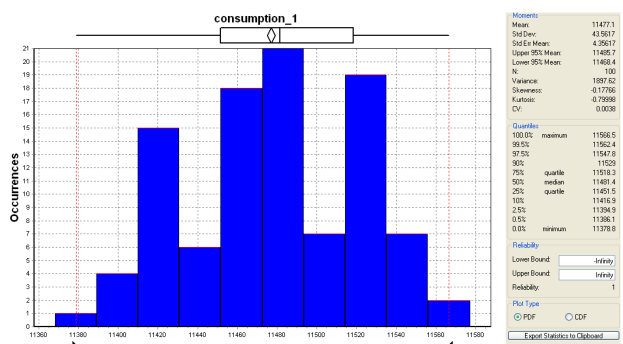


Figure F.45; Office System 2B (Capacity: system 2 x 3); Energy Consumption, 1st year, Mean 0.25

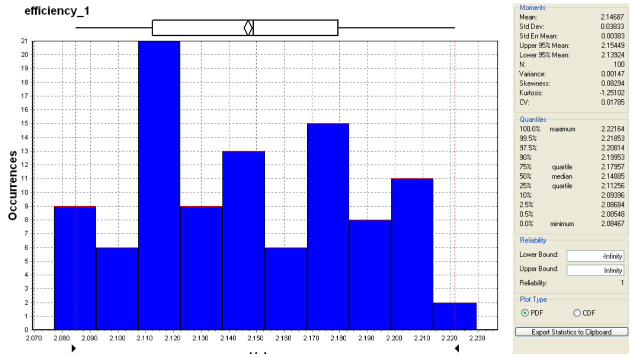


Figure F.46; Office System 2B (Capacity: system 2 x 3); Efficiency, 1st year, Mean 0.25

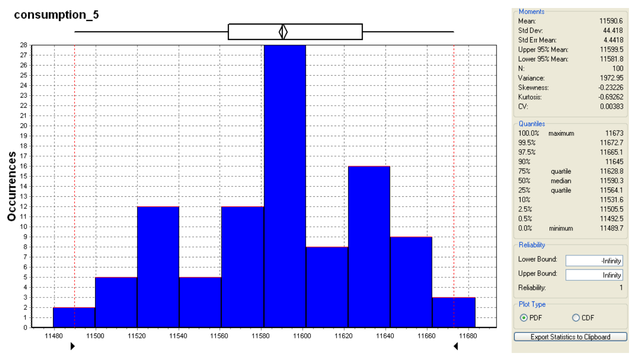


Figure F.47; Office System 2B (Capacity: system 2 x 3); Energy Consumption, 5 years average, Mean 0.25

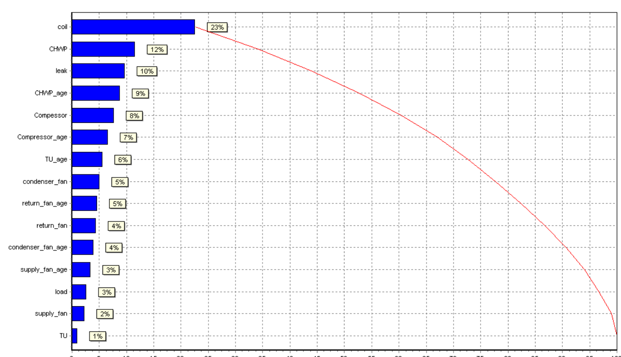


Figure F.48; Office System 2B (Capacity: system 2 x 3); Sensitivity analysis results, Mean 0.25

Table F.2; Office Systems 2, 2A, 2B; Component influence

| | | | |
|---|---|---|---|
| Compressor | 17.91 | 14.22 | 13.45 |
| Compressor age | 7.29 | 1.44 | 9.18 |
| Supply Fan | 2.57 | 9.19 | 7.90 |
| Supply Fan age | 2.28 | 8.92 | 10.54 |
| Return Fan | 9.01 | 2.80 | 5.17 |
| Return Fan age | 4.61 | 5.36 | 4.38 |
| Condenser Fan | 6.06 | 3.02 | 2.91 |
| Condenser Fan age | 6.81 | 3.18 | 5.99 |
| Chilled Water Pump | 5.26 | 2.09 | 10.29 |
| Chilled Water Pump age | 5.18 | 10.25 | 5.31 |
| Terminal Unit | 11.26 | 9.73 | 4.28 |
| Terminal Unit age | 3.54 | 4.76 | 8.17 |
| Leak | 3.03 | 4.27 | 3.21 |
| Load | 8.26 | 13.13 | 2.53 |
| Coil | 6.92 | 7.64 | 6.67 |

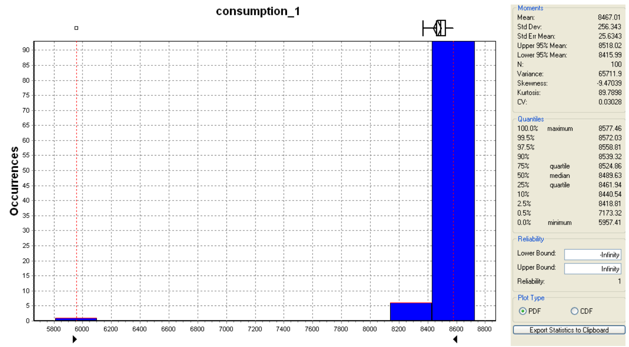

Figure F.49; Office System 3A (Capacity: system 3 x 2); Energy Consumption, 1st year, Mean 0.75

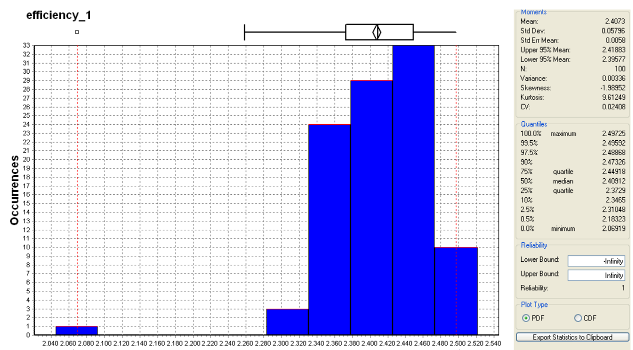

Figure F.50; Office System 3A (Capacity: system 3 x 2); Efficiency, 1st year, Mean 0.75

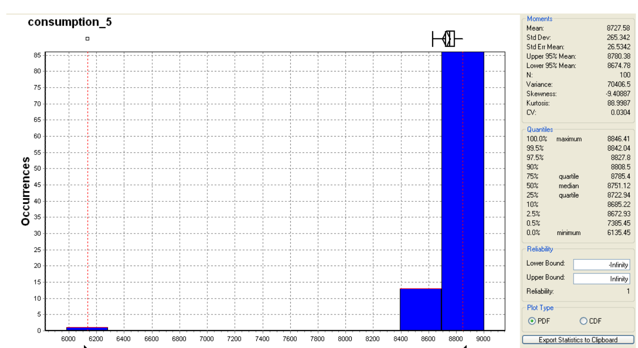

Figure F.51; Office System 3A (Capacity: system 3 x 2); Energy Consumption, 5 years average, Mean 0.75

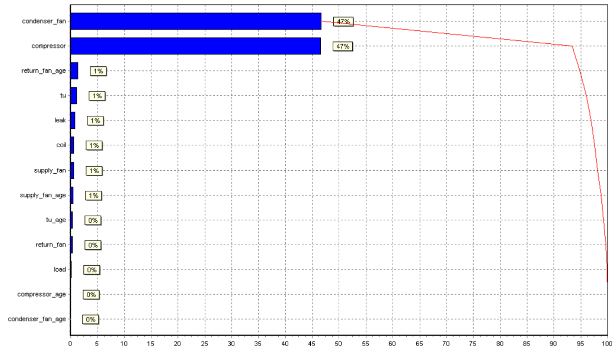


Figure F.52; Office System 3A (Capacity: system 3 x 2); Sensitivity analysis results, Mean 0.75

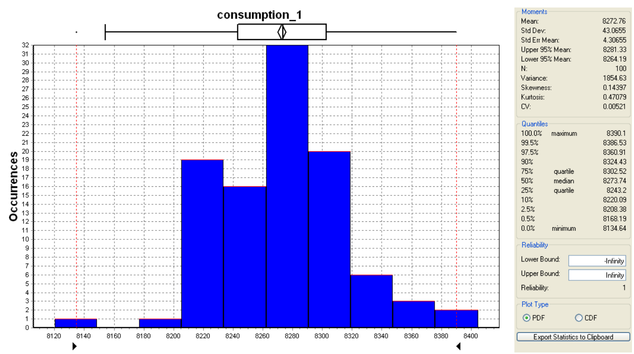


Figure F.53; Office System 3A (Capacity: system 3 x 2); Energy Consumption, 1st year, Mean 0.5

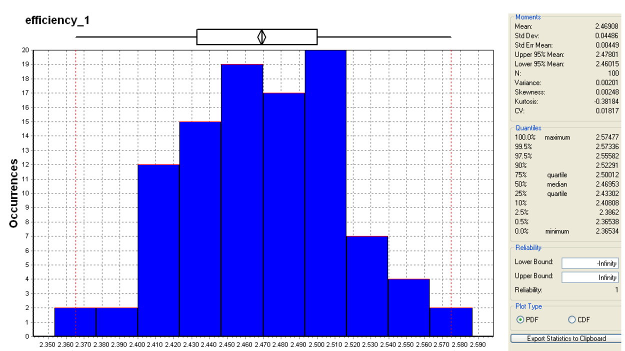


Figure F.54; Office System 3A (Capacity: system 3 x 2); Efficiency, 1st year, Mean 0.5

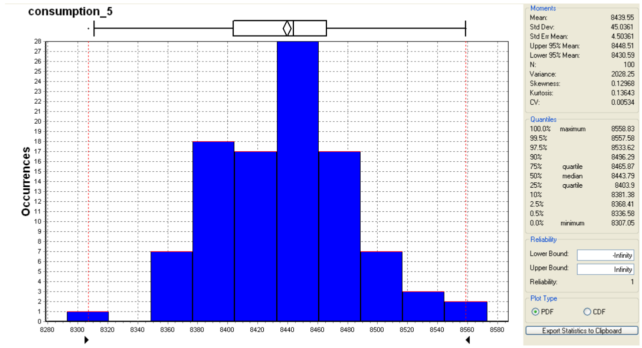


Figure F.55; Office System 3A (Capacity: system 3 x 2); Energy Consumption, 5 years average, Mean 0.5

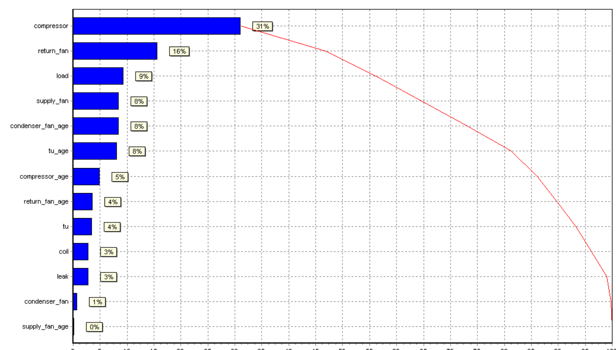


Figure F.56; Office System 3A (Capacity: system 3 x 2); Sensitivity analysis results, Mean 0.5

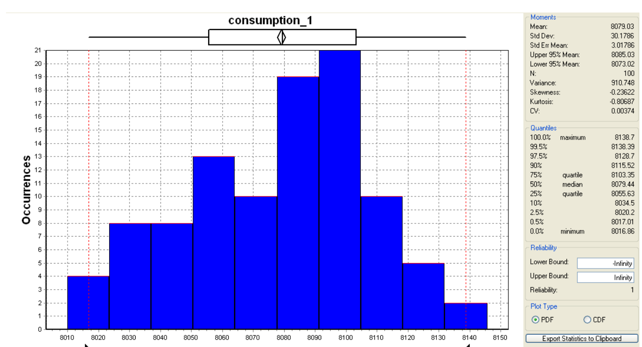


Figure F.57; Office System 3A (Capacity: system 3 x 2); Energy Consumption, 1st year, Mean 0.25

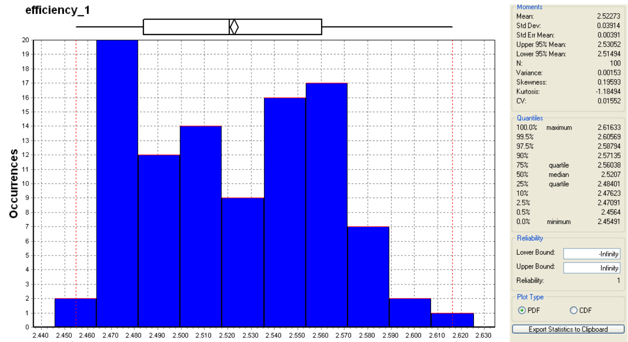

Figure F.58; Office System 3A (Capacity: system 3 x 2); Efficiency, 1st year, Mean 0.25

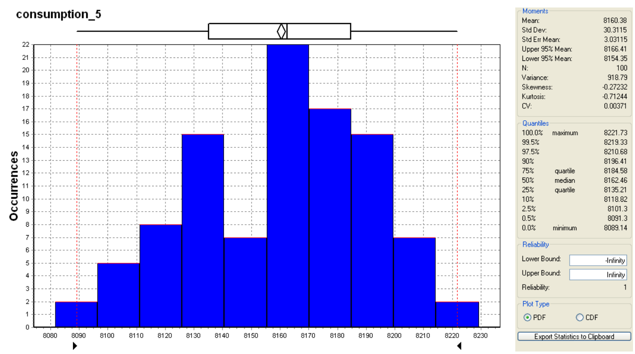

Figure F.59; Office System 3A (Capacity: system 3 x 2); Energy Consumption, 5 years average, Mean 0.25

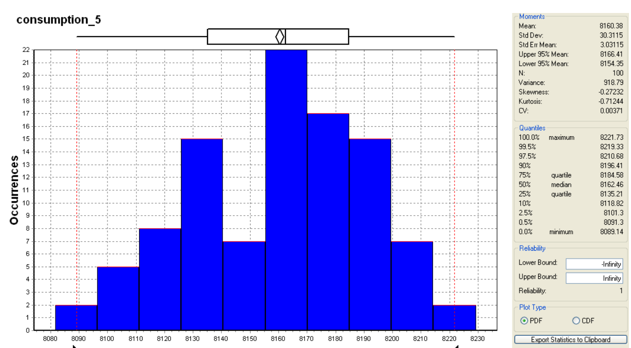

Figure F.60; Office System 3A (Capacity: system 3 x 2); Sensitivity analysis results, Mean 0.25

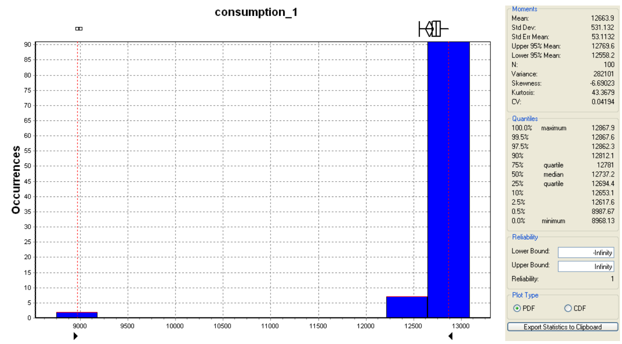


Figure F.61; Office System 3B (Capacity: system 3 x 3); Energy Consumption, 1st year, Mean 0.75

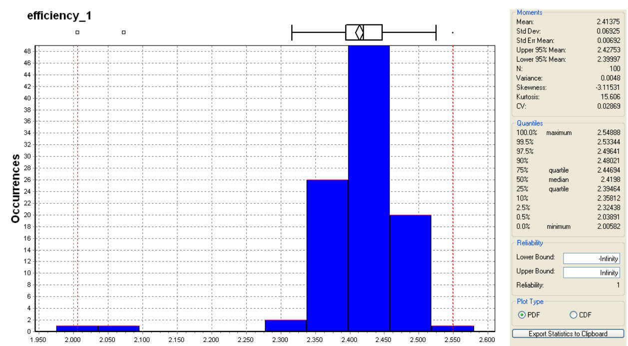


Figure F.62; Office System 3B (Capacity: system 3 x 3); Efficiency, 1st year, Mean 0.75

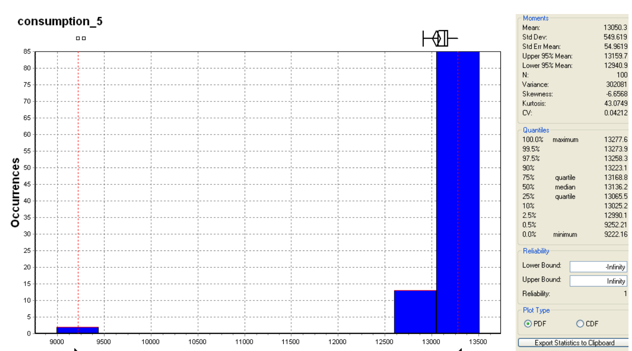


Figure F.63; Office System 3B (Capacity: system 3 x 3); Energy Consumption, 5 years average, Mean 0.75

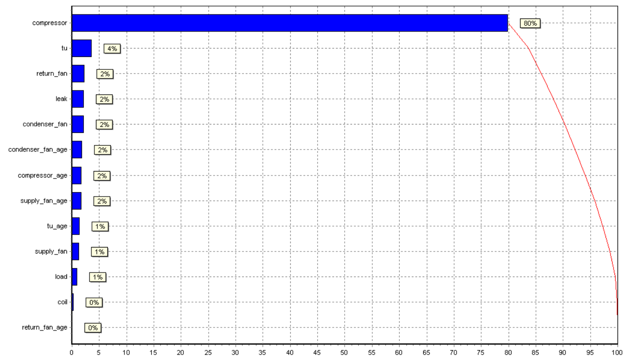


Figure F.64; Office System 3B (Capacity: system 3 x 3); Sensitivity analysis results, Mean 0.75

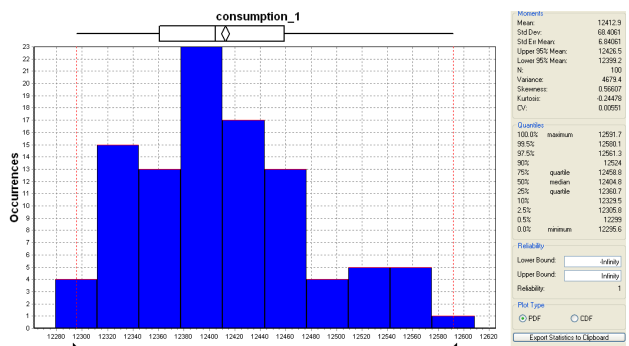


Figure F.65; Office System 3B (Capacity: system 3 x 3); Energy Consumption, 1st year, Mean 0.5

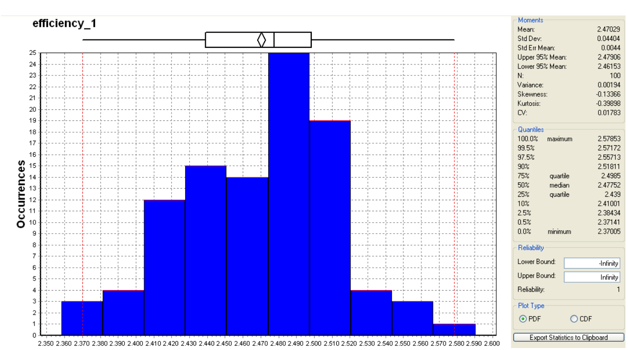


Figure F.66; Office System 3B (Capacity: system 3 x 3); Efficiency, 1st year, Mean 0.5

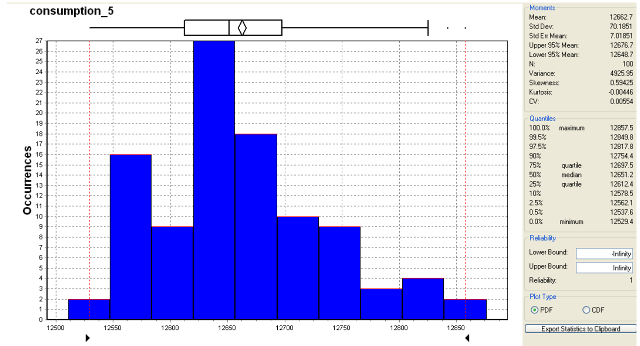

Figure F.67; Office System 3B (Capacity: system 3 x 3); Energy Consumption, 5 years average, Mean 0.5

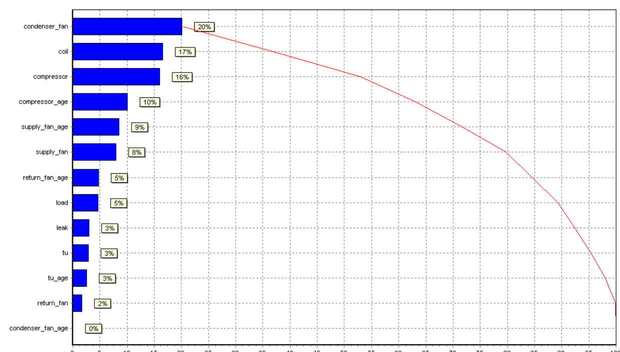

Figure F.68; Office System 3B (Capacity: system 3 x 3); Sensitivity analysis results, Mean 0.5

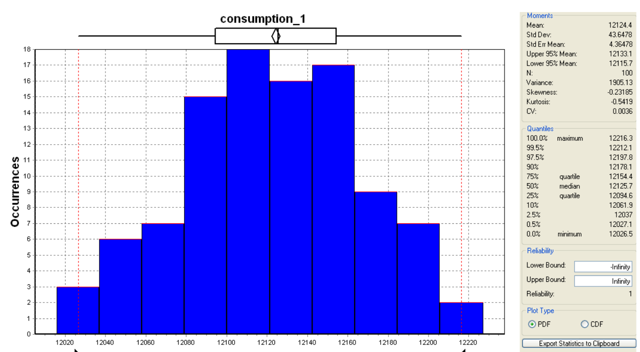

Figure F.69; Office System 3B (Capacity: system 3 x 3); Energy Consumption, 1st year, Mean 0.25

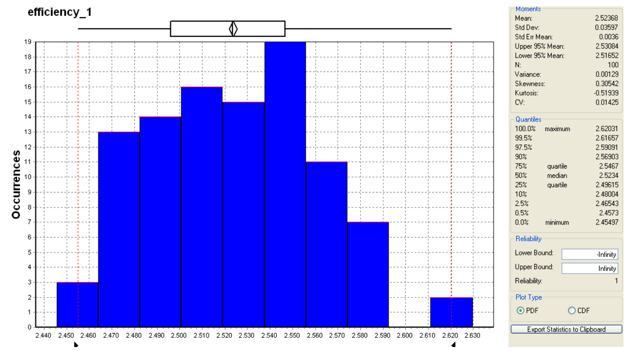

Figure F.70; Office System 3B (Capacity: system 3 x 3); Efficiency, 1st year, Mean 0.25

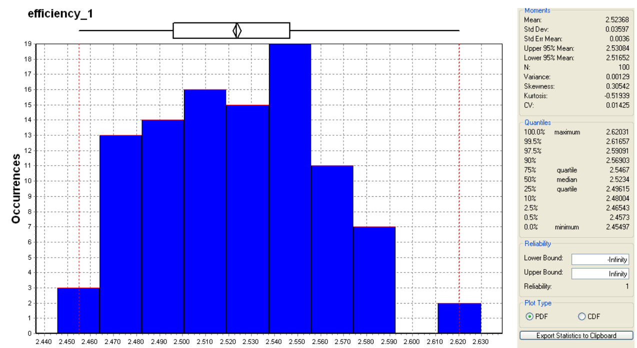

Figure F.71; Office System 3B (Capacity: system 3 x 3); Energy Consumption, 5 years average, Mean 0.25

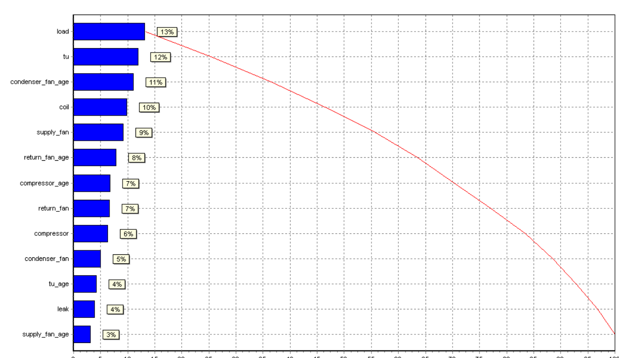

Figure F.72; Office System 3B (Capacity: system 3 x 3); Sensitivity analysis results, Mean 0.25

Table F.3; Office Systems 3, 3A, 3B; Component influence

| | | | |
|---|---|---|---|
| Compressor | 34.59 | 32.60 | 25.95 |
| Compressor age | 2.55 | 4.13 | 8.57 |
| Supply Fan | 1.72 | 7.13 | 6.85 |
| Supply Fan age | 16.35 | 1.13 | 7.66 |
| Return Fan | 3.33 | 13.16 | 2.12 |
| Return Fan age | 2.58 | 3.40 | 4.24 |
| Condenser Fan | 4.40 | 8.42 | 16.57 |
| Condenser Fan age | 7.06 | 6.78 | 0.62 |
| Terminal Unit | 2.15 | 3.43 | 3.38 |
| Terminal Unit age | 13.00 | 6.43 | 2.69 |
| Leak | 1.75 | 2.92 | 2.85 |
| Load | 1.21 | 7.51 | 4.54 |
| Coil | 9.32 | 2.95 | 13.97 |

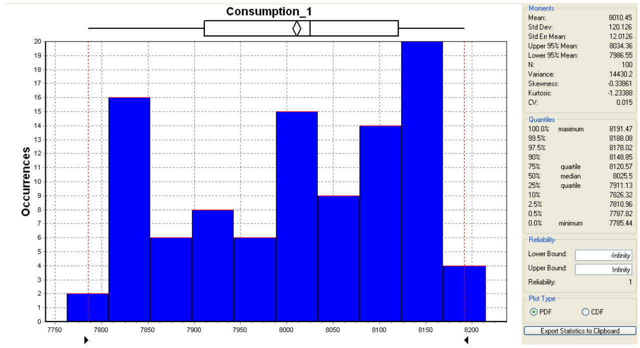

Figure F.73; Office System 4A (Capacity: system 4 x 2); Energy Consumption, 1st year, Mean 0.75

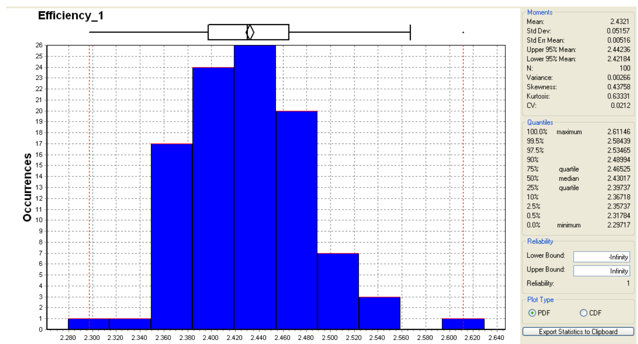

Figure F.74; Office System 4A (Capacity: system 4 x 2); Efficiency, 1st year, Mean 0.75

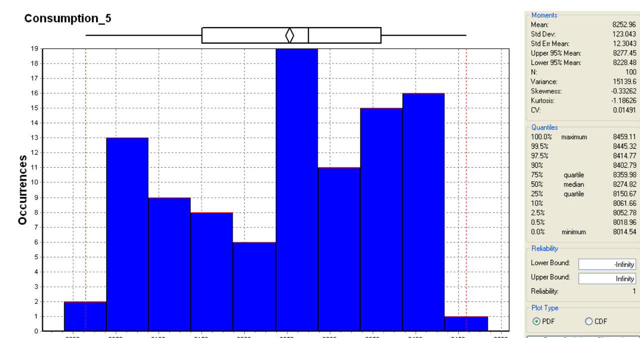

Figure F.75; Office System 4A (Capacity: system 4 x 2); Energy Consumption, 5 years average, Mean 0.75

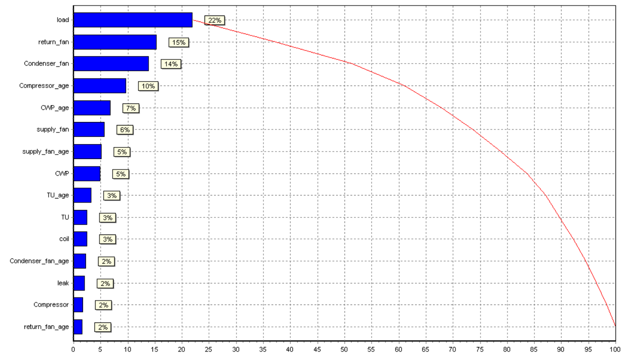

Figure F.76; Office System 4A (Capacity: system 4 x 2); Sensitivity analysis results, Mean 0.75

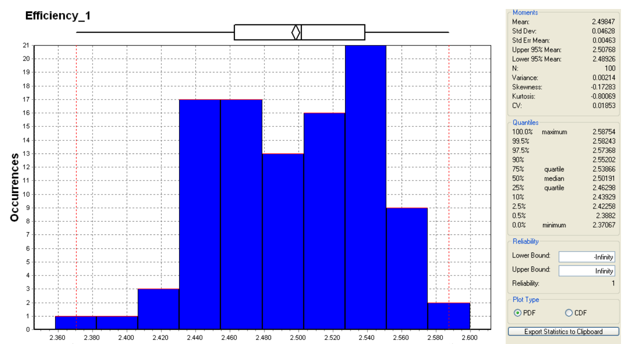

Figure F.77; Office System 4A (Capacity: system 4 x 2); Energy Consumption, 1st year, Mean 0.5

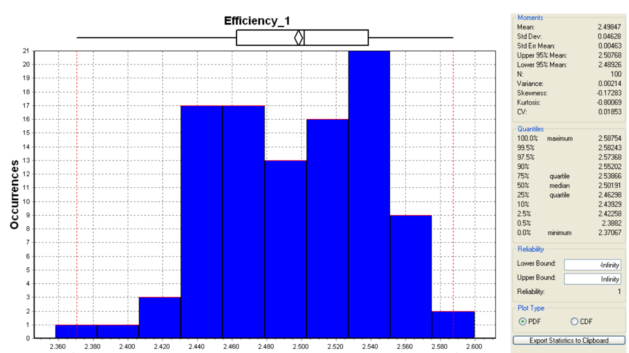

Figure F.78; Office System 4A (Capacity: system 4 x 2); Efficiency, 1st year, Mean 0.5

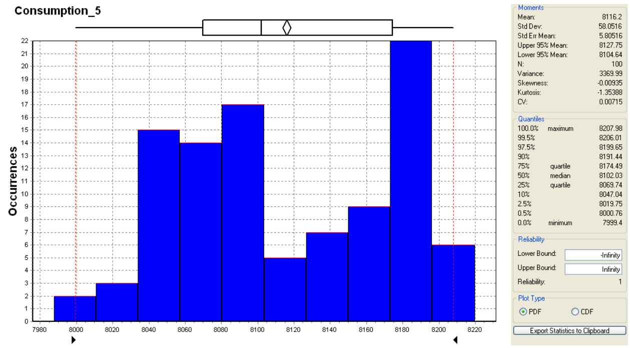


Figure F.79; Office System 4A (Capacity: system 4 x 2); Energy Consumption, 5 years average, Mean 0.5

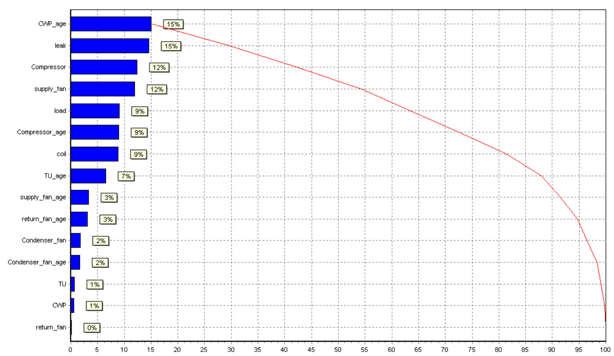


Figure F.80; Office System 4A (Capacity: system 4 x 2); Sensitivity analysis results, Mean 0.5

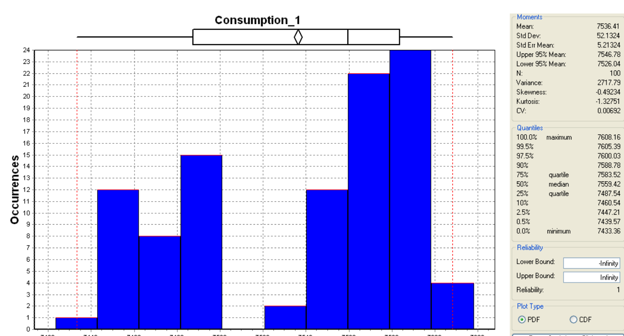


Figure F.81; Office System 4A (Capacity: system 4 x 2); Energy Consumption, 1st year, Mean 0.25

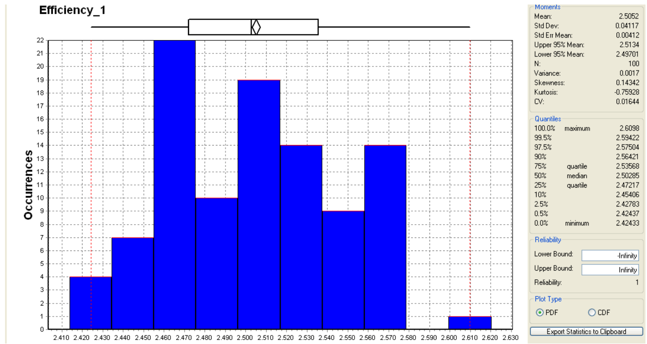


Figure F.82; Office System 4A (Capacity: system 4 x 2); Efficiency, 1st year, Mean 0.25

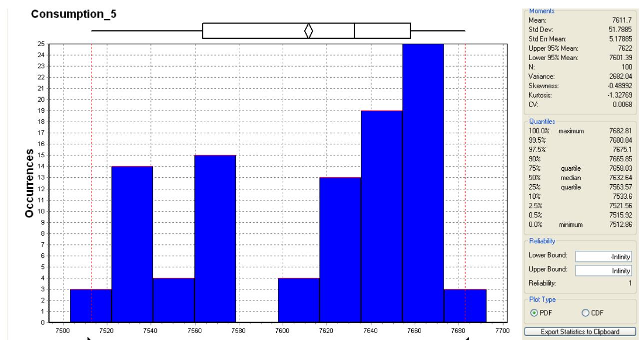


Figure F.83; Office System 4A (Capacity: system 4 x 2); Energy Consumption, 5 years average, Mean 0.25

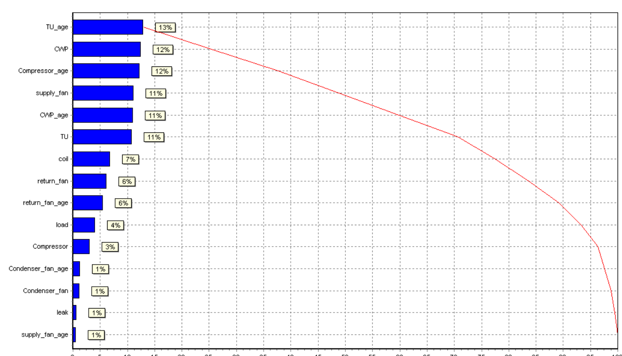


Figure F.84; Office System 4A (Capacity: system 4 x 2); Sensitivity analysis results, Mean 0.25

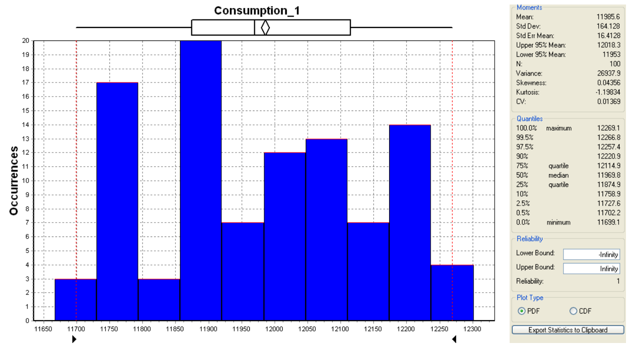

Figure F.85; Office System 4B (Capacity: system 4 x 3); Energy Consumption, 1st year, Mean 0.75

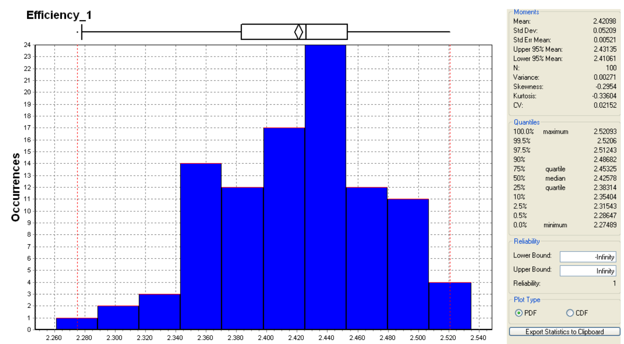

Figure F.86; Office System 4B (Capacity: system 4 x 3); Efficiency, 1st year, Mean 0.75

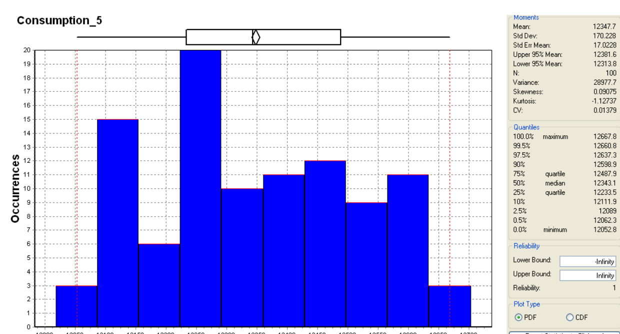

Figure F.87; Office System 4B (Capacity: system 4 x 3); Energy Consumption, 5 years average, Mean 0.75

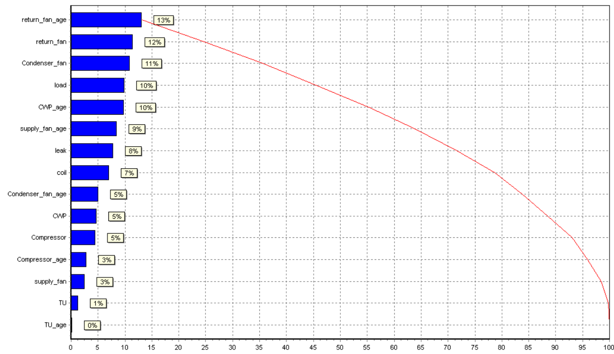


Figure F.88; Office System 4B (Capacity: system 4 x 3); Sensitivity analysis results, Mean 0.75

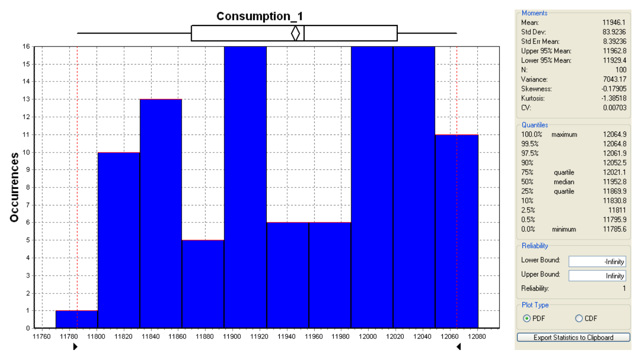


Figure F.89; Office System 4B (Capacity: system 4 x 3); Energy Consumption, 1st year, Mean 0.5

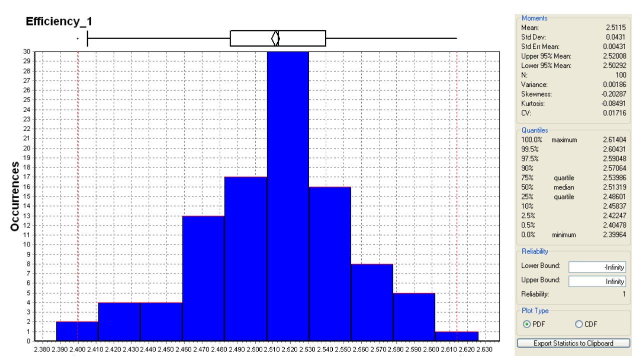


Figure F.90; Office System 4B (Capacity: system 4 x 3); Efficiency, 1st year, Mean 0.5

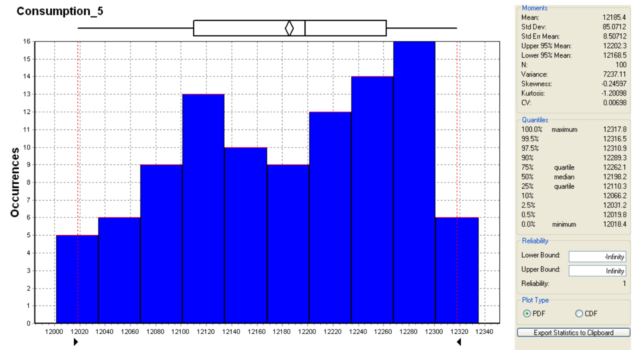


Figure F.91; Office System 4B (Capacity: system 4 x 3); Energy Consumption, 5 years average, Mean 0.5

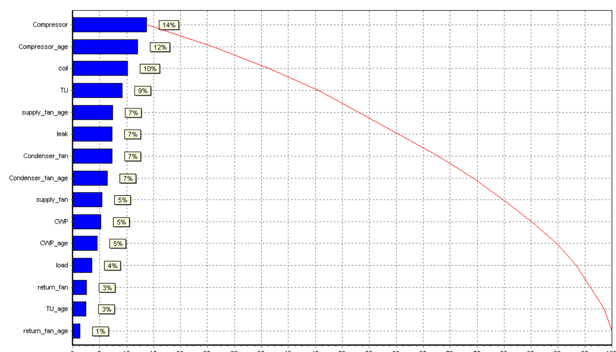

Figure F.92; Office System 4B (Capacity: system 4 x 3); Sensitivity analysis results, Mean 0.5

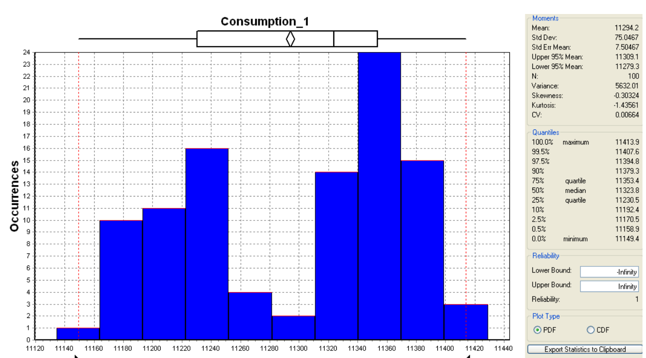


Figure F.93; Office System 4B (Capacity: system 4 x 3); Energy Consumption, 1st year, Mean 0.25

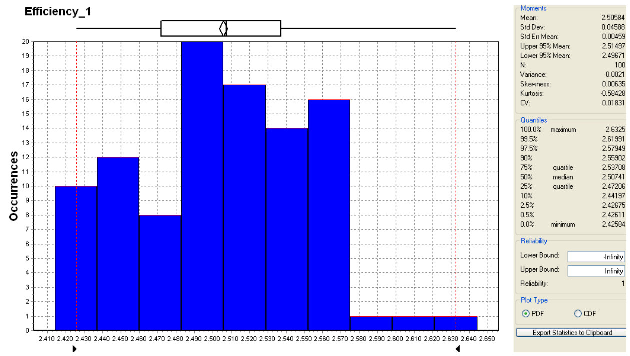


Figure F.94; Office System 4B (Capacity: system 4 x 3); Efficiency, 1st year, Mean 0.25

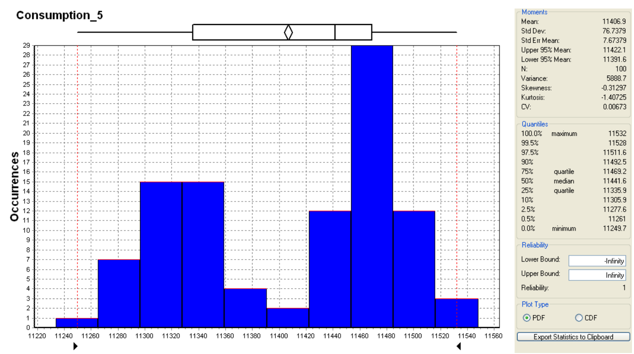


Figure F.95; Office System 4B (Capacity: system 4 x 3); Energy Consumption, 5 years average, Mean 0.25

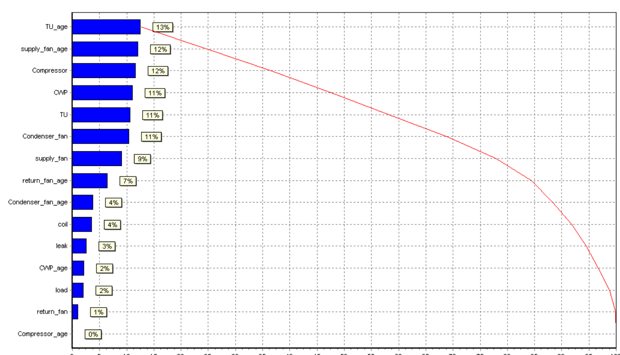


Figure F.96; Office System 4B (Capacity: system 4 x 3); Sensitivity analysis results, Mean 0.25

Table F.4; Office Systems 4, 4A, 4B; Component influence

| | | | |
|---|---|---|---|
| Chiller | 22.69 | 10.12 | 12.54 |
| Chiller age | 4.99 | 9.23 | 10.26 |
| Supply Fan | 6.06 | 10.98 | 4.80 |
| Supply Fan age | 1.02 | 3.26 | 7.49 |
| Return Fan | 9.68 | 2.59 | 4.42 |
| Return Fan age | 4.21 | 2.91 | 3.12 |
| Condenser Fan | 3.62 | 3.91 | 7.79 |
| Condenser Fan age | 6.03 | 1.97 | 6.62 |
| Chilled Water Pump | 3.43 | 1.94 | 5.18 |
| Chilled Water Pump age | 7.96 | 13.57 | 5.75 |
| Fan Coil Unit | 0.88 | 1.59 | 7.79 |
| Fan Coil Unit age | 10.14 | 6.50 | 2.80 |
| Leak | 6.97 | 12.49 | 7.08 |
| Load | 4.96 | 10.96 | 4.94 |
| Coil | 7.35 | 7.96 | 9.39 |

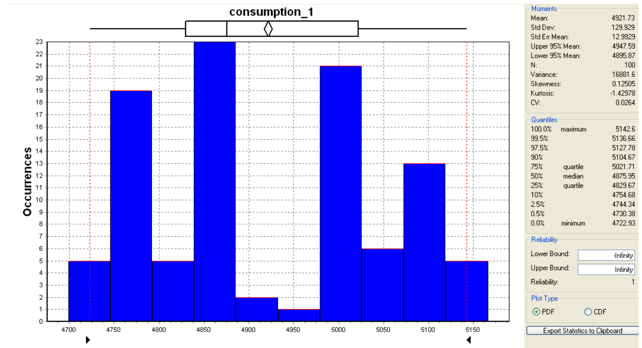

Figure F.97; Office System 5A (Capacity: system 5 x 2); Energy Consumption, 1st year, Mean 0.75

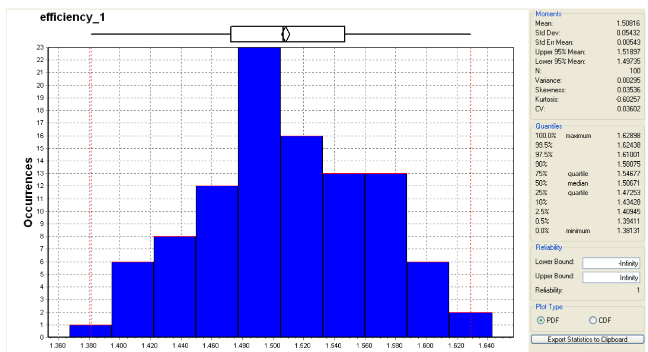

Figure F.98; Office System 5A (Capacity: system 5 x 2); Efficiency, 1st year, Mean 0.75

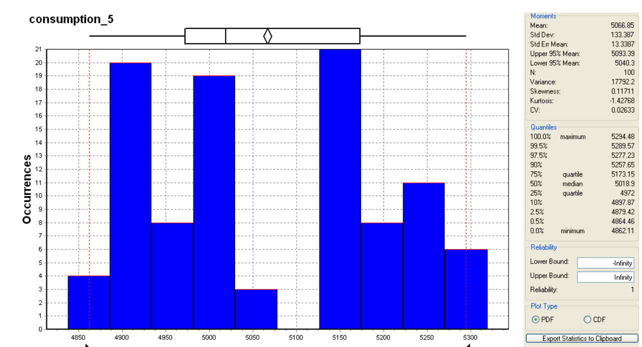

Figure F.99; Office System 5A (Capacity: system 5 x 2); Energy Consumption, 5 years average, Mean 0.75

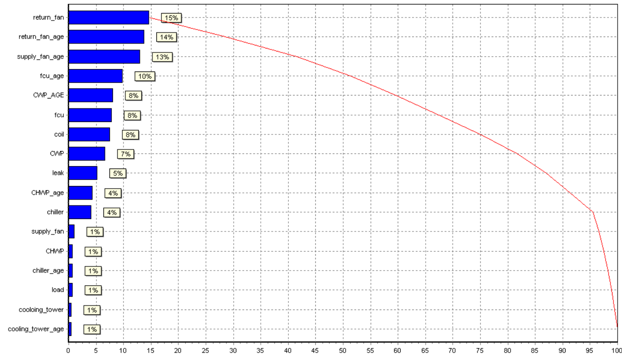


Figure F.100; Office System 5A (Capacity: system 5 x 2); Sensitivity analysis results, Mean 0.75

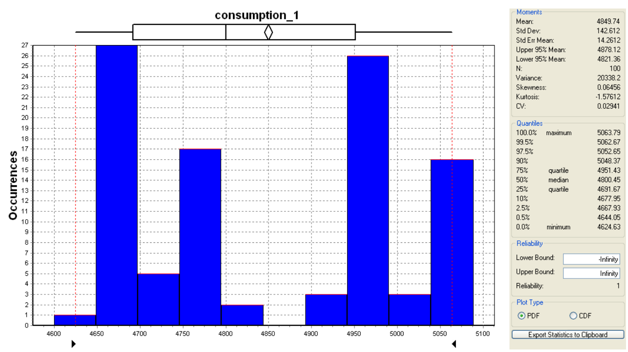


Figure F.101; Office System 5A (Capacity: system 5 x 2); Energy Consumption, 1st year, Mean 0.5

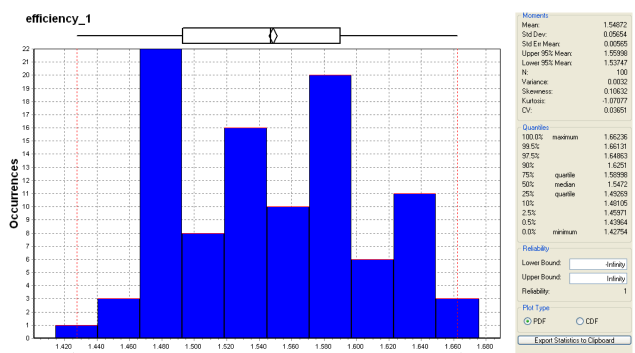


Figure F.102; Office System 5A (Capacity: system 5 x 2); Efficiency, 1st year, Mean 0.5

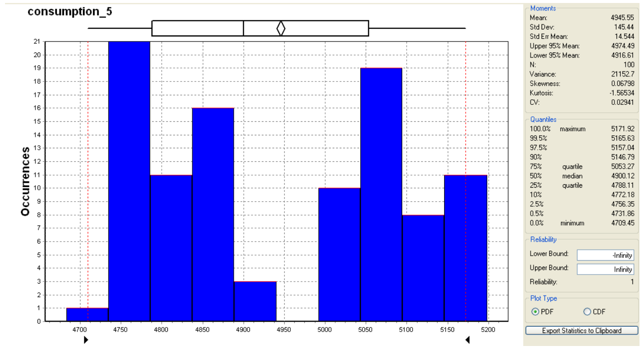


Figure F.103; Office System 5A (Capacity: system 5 x 2); Energy Consumption, 5 years average, Mean 0.5

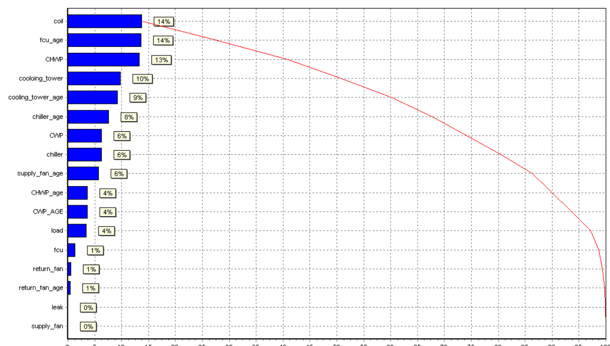


Figure F.104; Office System 5A (Capacity: system 5 x 2); Sensitivity analysis results, Mean 0.5

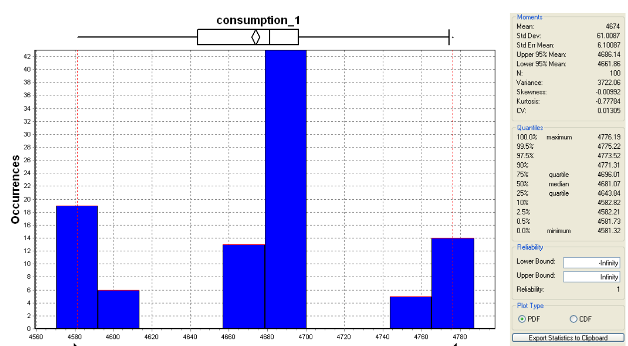


Figure F.105; Office System 5A (Capacity: system 5 x 2); Energy Consumption, 1st year, Mean 0.25

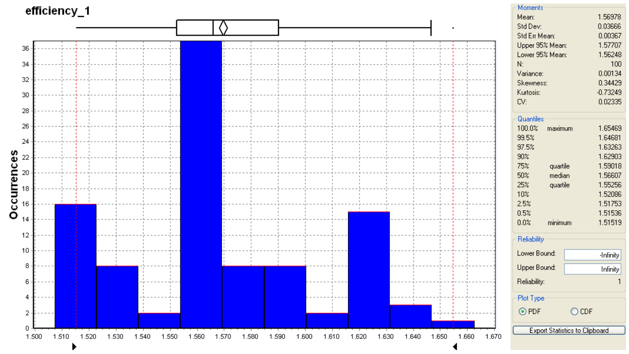


Figure F.106; Office System 5A (Capacity: system 5 x 2); Efficiency, 1st year, Mean 0.25

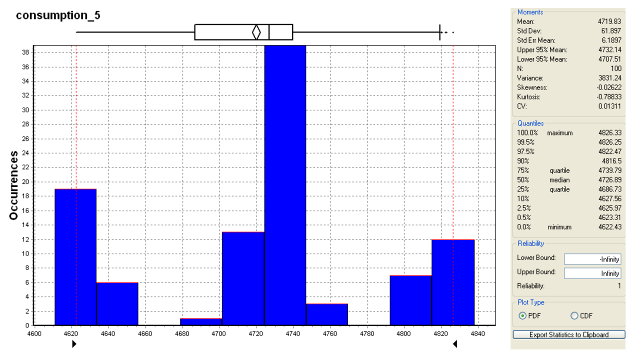


Figure F.107; Office System 5A (Capacity: system 5 x 2); Energy Consumption, 5 years average, Mean 0.25

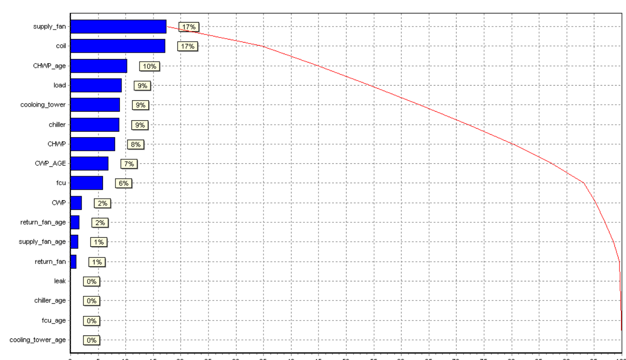

Figure F.108; Office System 5A (Capacity: system 5 x 2); Sensitivity analysis results, Mean 0.25

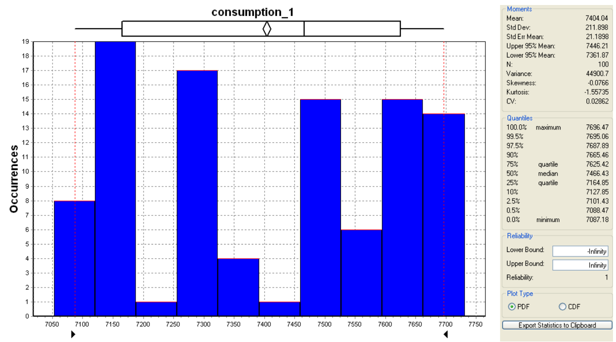


Figure F.109; Office System 5B (Capacity: system 5 x 3); Energy Consumption, 1st year, Mean 0.75

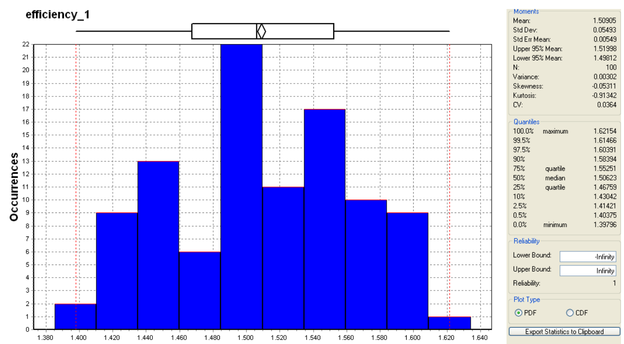


Figure F.110; Office System 5B (Capacity: system 5 x 3); Efficiency, 1st year, Mean 0.75

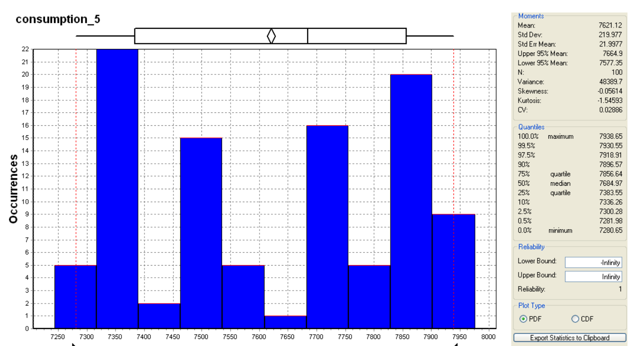


Figure F.111; Office System 5B (Capacity: system 5 x 3); Energy Consumption, 5 years average, Mean 0.75

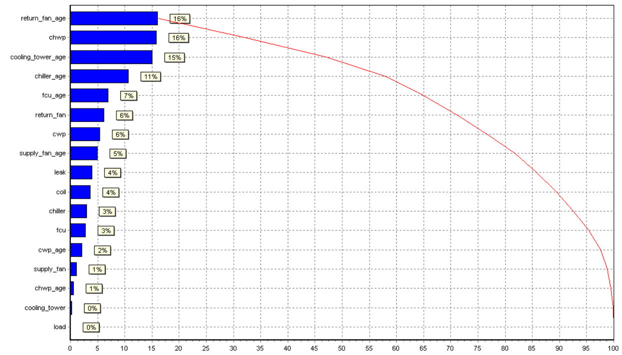


Figure F.112; Office System 5B (Capacity: system 5 x 3); Sensitivity analysis results, Mean 0.75

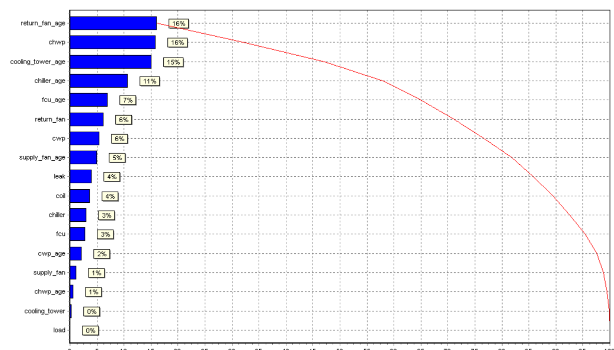


Figure F.113; Office System 5B (Capacity: system 5 x 3); Energy Consumption, 1st year, Mean 0.5

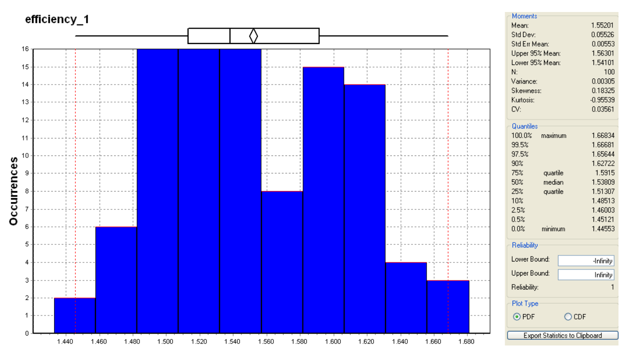


Figure F.114; Office System 5B (Capacity: system 5 x 3); Efficiency, 1st year, Mean 0.5

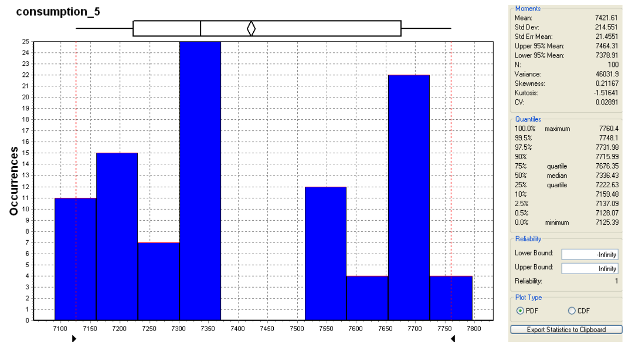

Figure F.115; Office System 5B (Capacity: system 5 x 3); Energy Consumption, 5 years average, Mean 0.5

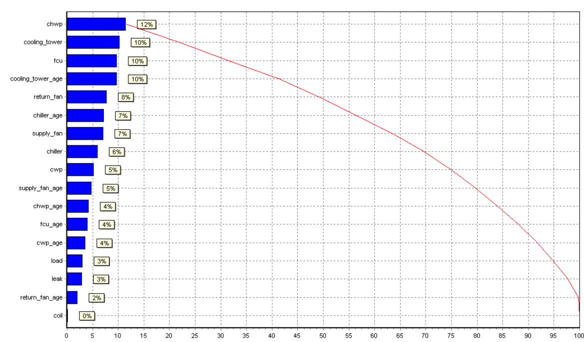

Figure F.116; Office System 5B (Capacity: system 5 x 3); Sensitivity analysis results, Mean 0.5

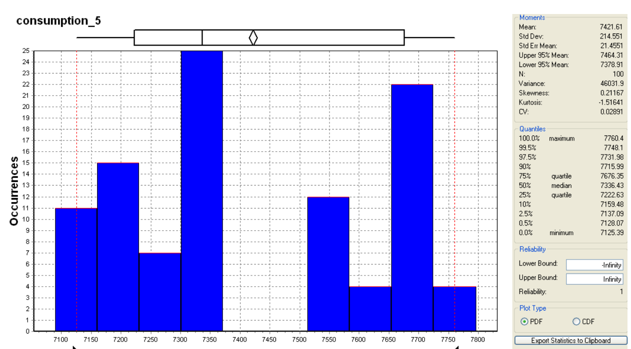

Figure F.117; Office System 5B (Capacity: system 5 x 3); Energy Consumption, 1st year, Mean 0.25

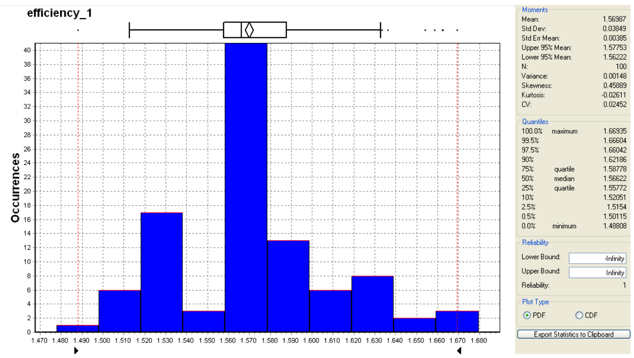

Figure F.118; Office System 5B (Capacity: system 5 x 3); Efficiency, $1^{st}$ year, Mean 0.25

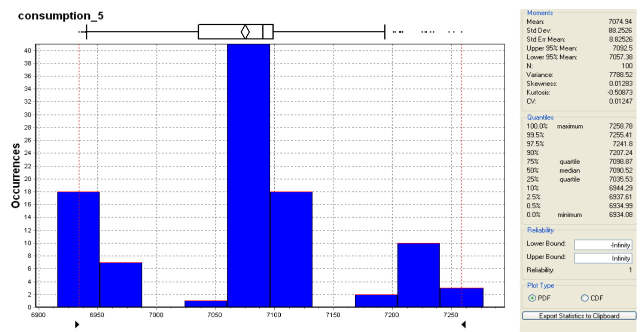

Figure F.119; Office System 5B (Capacity: system 5 x 3); Energy Consumption, 5 years average, Mean 0.25

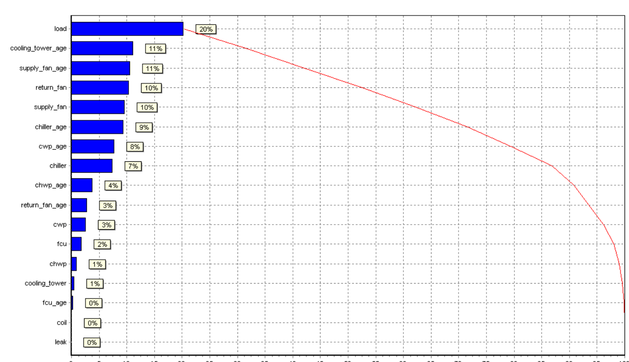

Figure F.120; Office System 5B (Capacity: system 5 x 3); Sensitivity analysis results, Mean 0.25

Table F.5; Office Systems 5, 5A, 5B; Component influence

| | | | |
|---|---|---|---|
| Chiller | 7.10 | 5.69 | 5.55 |
| Chiller age | 0.84 | 6.57 | 7.72 |
| Supply Fan | 0.35 | 0.61 | 6.12 |
| Supply Fan age | 6.64 | 7.07 | 5.17 |
| Return Fan | 5.93 | 3.23 | 7.74 |
| Return Fan age | 6.86 | 3.10 | 4.30 |
| Cooling Tower | 5.74 | 8.41 | 8.15 |
| Cooling Tower age | 5.58 | 7.37 | 10.86 |
| Chilled Water Pump | 5.71 | 10.78 | 12.37 |
| Chilled Water Pump age | 7.43 | 4.11 | 3.52 |
| Condenser Water Pump | 7.40 | 5.98 | 4.95 |
| Condenser Water Pump age | 1.82 | 4.67 | 3.79 |
| Fan Coil Unit | 3.89 | 2.24 | 8.66 |
| Fan Coil Unit age | 7.94 | 12.81 | 4.39 |
| Leak | 11.81 | 0.80 | 3.09 |
| Load | 3.32 | 3.60 | 2.98 |
| Coil | 11.64 | 12.95 | 0.65 |

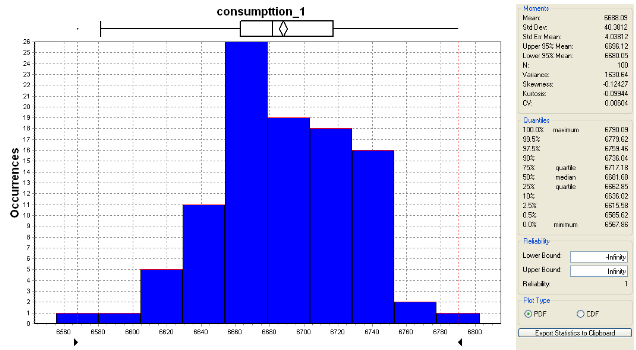

Figure F.121; Office System 6A (Capacity: system 6 x 2); Energy Consumption, 1st year, Mean 0.75

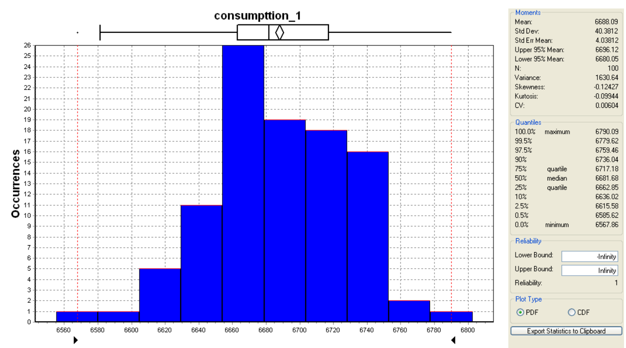

Figure F.122; Office System 6A (Capacity: system 6 x 2); Efficiency, 1st year, Mean 0.75

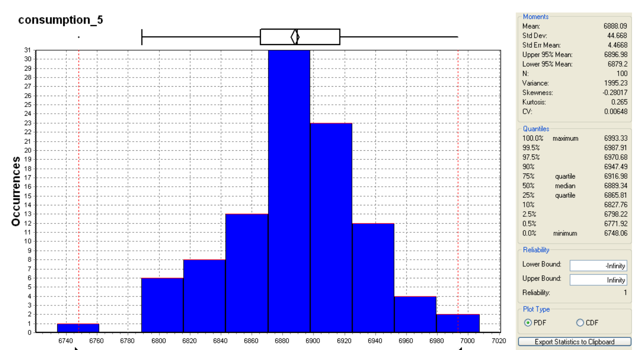

Figure F.123; Office System 6A (Capacity: system 6 x 2); Energy Consumption, 5 years average, Mean 0.75

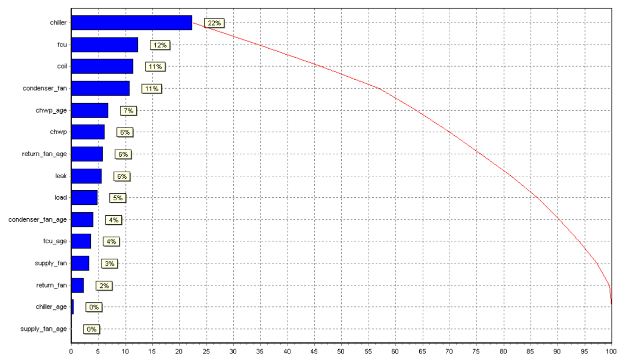


Figure F.124; Office System 6A (Capacity: system 6 x 2); Sensitivity analysis results, Mean 0.75

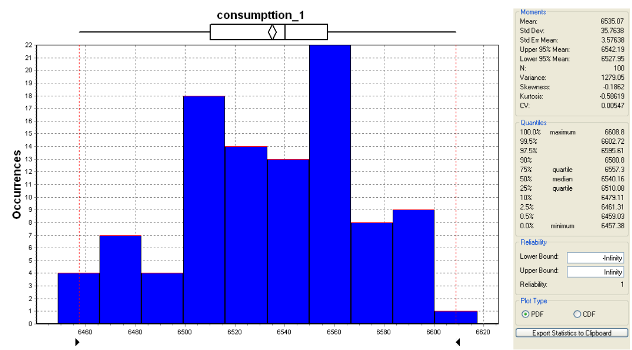


Figure F.125; Office System 6A (Capacity: system 6 x 2); Energy Consumption, 1st year, Mean 0.5

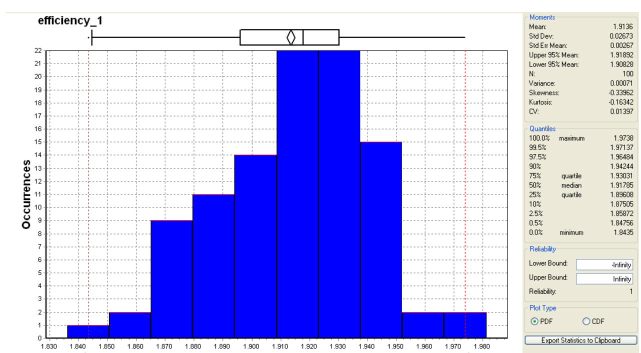


Figure F.126; Office System 6A (Capacity: system 6 x 2); Efficiency, 1st year, Mean 0.5

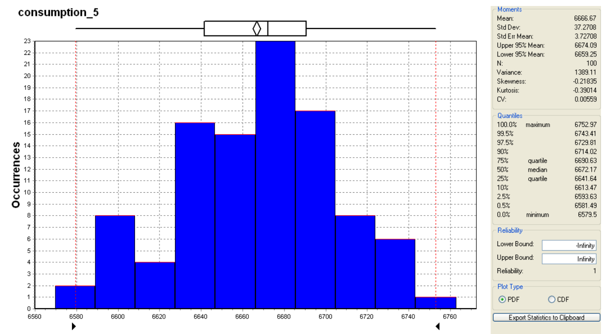


Figure F.127; Office System 6A (Capacity: system 6 x 2); Energy Consumption, 5 years average, Mean 0.5

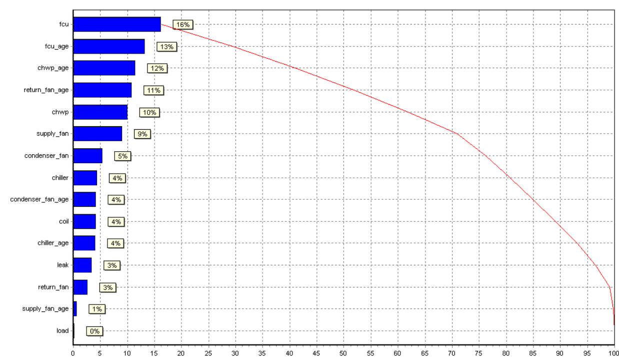


Figure F.128; Office System 6A (Capacity: system 6 x 2); Sensitivity analysis results, Mean 0.5

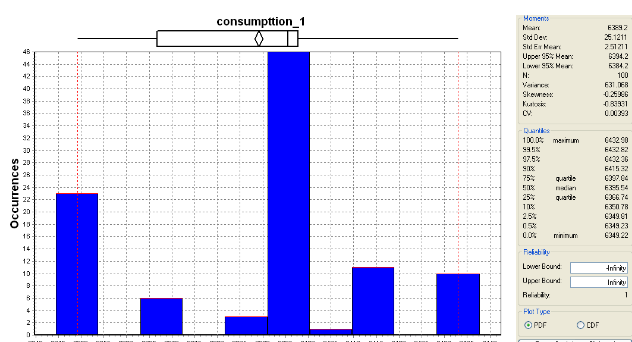


Figure F.129; Office System 6A (Capacity: system 6 x 2); Energy Consumption, 1st year, Mean 0.25

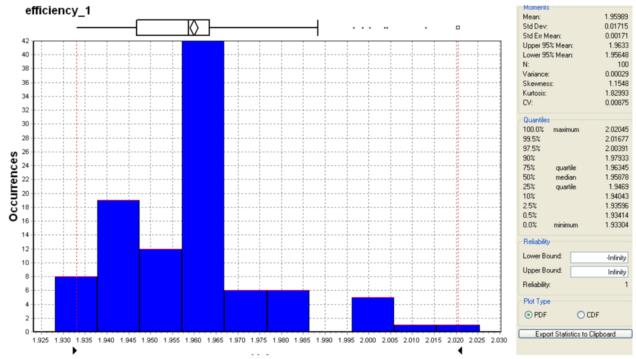

Figure F.130; Office System 6A (Capacity: system 6 x 2); Efficiency, 1st year, Mean 0.25

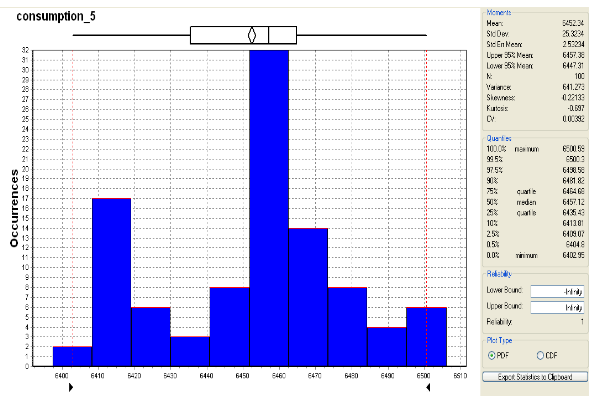

Figure F.131; Office System 6A (Capacity: system 6 x 2); Energy Consumption, 5 years average, Mean 0.25

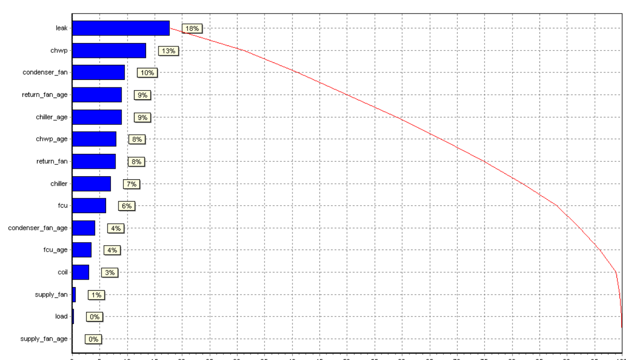

Figure F.132; Office System 6A (Capacity: system 6 x 2); Sensitivity analysis results, Mean 0.25

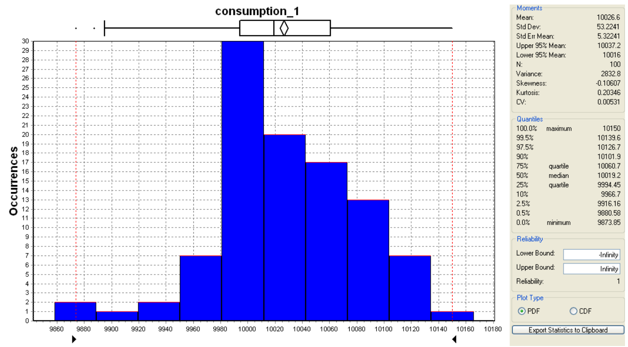


Figure F.133; Office System 6B (Capacity: system 6 x 3); Energy Consumption, 1st year, Mean 0.75

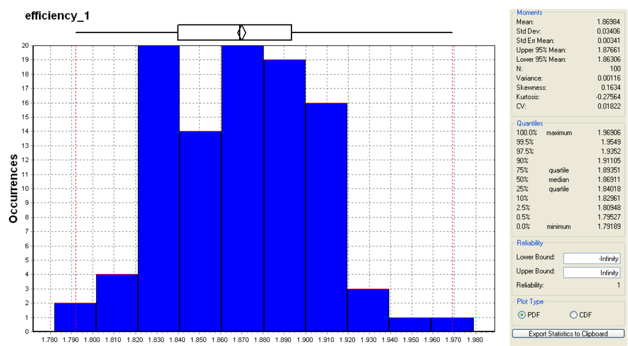


Figure F.134; Office System 6B (Capacity: system 6 x 3); Efficiency, 1st year, Mean 0.75

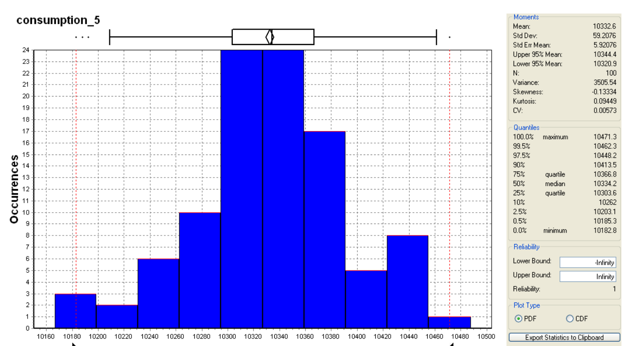


Figure F.135; Office System 6B (Capacity: system 6 x 3); Energy Consumption, 5 years average, Mean 0.75

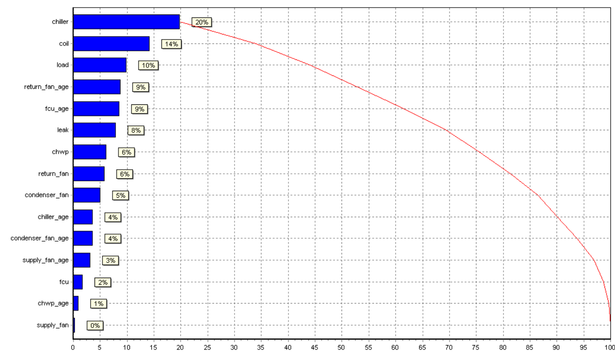


Figure F.136; Office System 6B (Capacity: system 6 x 3); Sensitivity analysis results, Mean 0.75

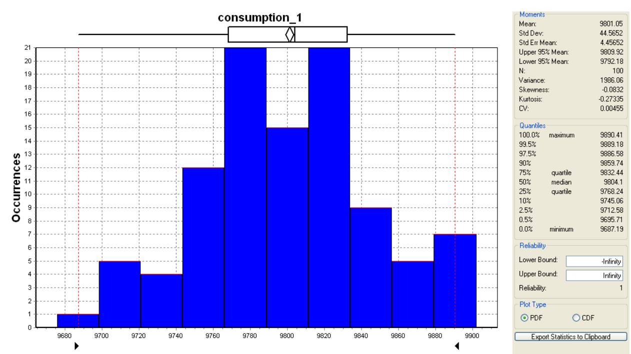


Figure F.137; Office System 6B (Capacity: system 6 x 3); Energy Consumption, 1st year, Mean 0.5

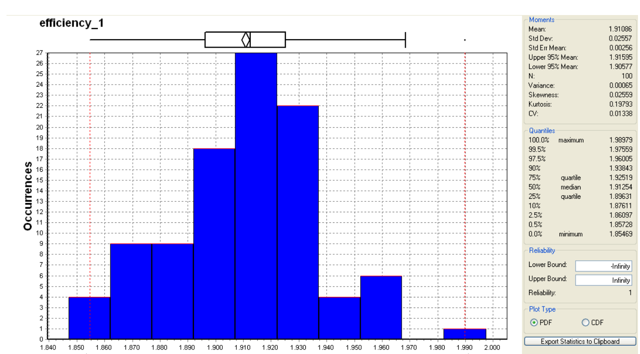


Figure F.138; Office System 6B (Capacity: system 6 x 3); Efficiency, 1st year, Mean 0.5

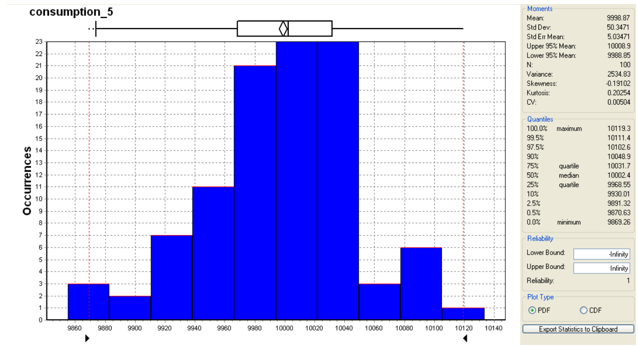

Figure F.139; Office System 6B (Capacity: system 6 x 3); Energy Consumption, 5 years average, Mean 0.5

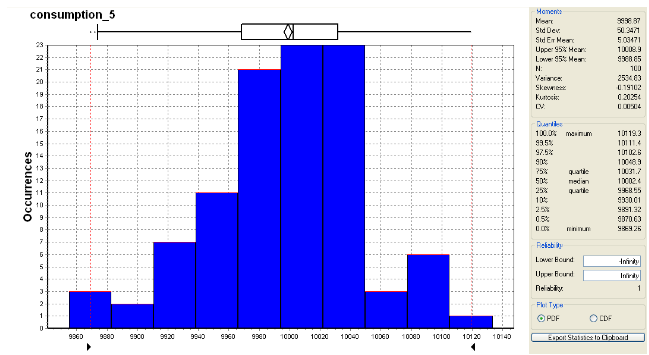

Figure F.140; Office System 6B (Capacity: system 6 x 3); Sensitivity analysis results, Mean 0.5

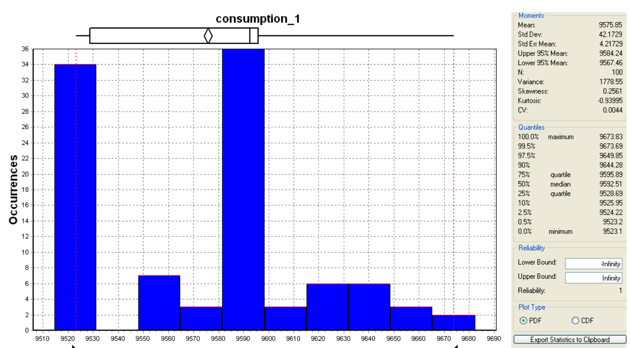

Figure F.141; Office System 6B (Capacity: system 6 x 3); Energy Consumption, 1st year, Mean 0.25

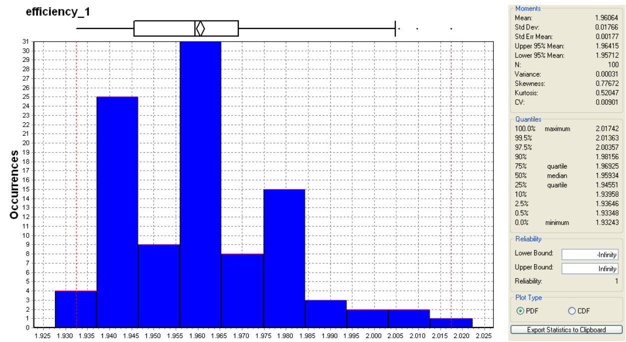


Figure F.142; Office System 6B (Capacity: system 6 x 3); Efficiency, 1$^{st}$ year, Mean 0.25

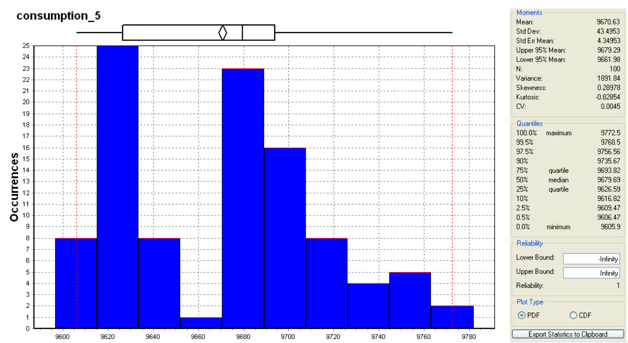


Figure F.143; Office System 6B (Capacity: system 6 x 3); Energy Consumption, 5 years average, Mean 0.25

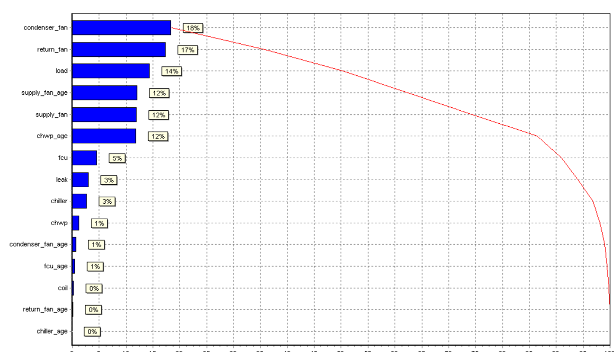


Figure F.144; Office System 6B (Capacity: system 6 x 3); Sensitivity analysis results, Mean 0.25

Table F.6; Office Systems 6, 6A, 6B; Component influence

| | | | |
|---|---|---|---|
| Compressor | 12.18 | 7.06 | 15.72 |
| Compressor age | 10.72 | 3.51 | 6.42 |
| Supply Fan | 0.91 | 7.87 | 6.91 |
| Supply Fan age | 5.32 | 0.82 | 4.94 |
| Return Fan | 12.37 | 3.00 | 10.51 |
| Return Fan age | 2.14 | 10.22 | 3.13 |
| Condenser Fan | 11.74 | 6.16 | 10.37 |
| Condenser Fan age | 0.60 | 4.03 | 4.80 |
| Chilled Water Pump | 5.43 | 9.67 | 1.02 |
| Chilled Water Pump age | 6.25 | 11.17 | 4.61 |
| Terminal Unit | 9.19 | 15.20 | 11.17 |
| Terminal Unit age | 1.15 | 11.39 | 2.33 |
| Leak | 15.50 | 3.92 | 5.51 |
| Load | 6.01 | 0.82 | 2.03 |
| Coil | 0.49 | 5.15 | 10.53 |

# APPENDIX G

# COMPONENTS CORRELATION WITH CAPACITY

Table G.1; System 1 (office) component sensitivity with system capacity changes

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 150 Tons | | | | | 300 Tons | | | | | 450 Tons | | | |
| System 1 | 25 | 50 | 75 | Average | % | 25 | 50 | 75 | Average | % | 25 | 50 | 75 | Average | % |
| Chiller | 8 | 8 | 8 | 29.6 | 8.07 | 8 | 9 | 12 | 35 | 9.60 | 0 | 2 | 9 | 11.4 | 3.03 |
| Chiller age | 5 | 11 | 8 | 38.3 | 10.44 | 12 | 2 | 2 | 8.4 | 2.30 | 13 | 3 | 6 | 13.9 | 3.69 |
| Supply Fan | 3 | 3 | 7 | 13.5 | 3.68 | 8 | 12 | 12 | 44 | 12.06 | 7 | 5 | 2 | 16.9 | 4.49 |
| Supply Fan age | 2 | 2 | 3 | 8 | 2.18 | 2 | 1 | 2 | 4.4 | 1.21 | 3 | 6 | 6 | 21.9 | 5.82 |
| Return Fan | 10 | 1 | 1 | 4.6 | 1.25 | 5 | 9 | 7 | 31.7 | 8.69 | 2 | 3 | 2 | 10.4 | 2.76 |
| Return Fan age | 1 | 5 | 10 | 21.1 | 5.75 | 1 | 5 | 10 | 21.1 | 5.79 | 5 | 12 | 7 | 40.7 | 10.81 |
| Cooling Tower | 7 | 5 | 7 | 19.9 | 5.42 | 1 | 1 | 14 | 11.5 | 3.15 | 5 | 13 | 3 | 41.3 | 10.97 |
| Cooling Tower age | 8 | 1 | 9 | 9.2 | 2.51 | 3 | 4 | 10 | 18.3 | 5.02 | 6 | 3 | 5 | 12.6 | 3.35 |
| Chilled Water Pump | 8 | 8 | 10 | 30.8 | 8.39 | 9 | 5 | 4 | 18.3 | 5.02 | 8 | 13 | 8 | 44.6 | 11.85 |
| Chilled Water Pump age | 6 | 8 | 11 | 31.2 | 8.50 | 3 | 10 | 5 | 33.3 | 9.13 | 1 | 15 | 7 | 49.3 | 13.09 |
| Condenser Water Pump | 1 | 3 | 4 | 11.5 | 3.13 | 10 | 5 | 12 | 23.2 | 6.36 | 1 | 1 | 9 | 8.5 | 2.26 |
| Condenser Water Pump a | 3 | 7 | 7 | 25.5 | 6.95 | 6 | 5 | 3 | 17.4 | 4.77 | 3 | 10 | 1 | 30.9 | 8.21 |
| Terminal Unit | 5 | 4 | 0 | 12.5 | 3.41 | 9 | 5 | 0 | 15.9 | 4.36 | 12 | 6 | 11 | 25.8 | 6.85 |
| Terminal Unit age | 5 | 4 | 12 | 19.7 | 5.37 | 5 | 4 | 12 | 19.7 | 5.40 | 6 | 1 | 7 | 7.8 | 2.07 |
| Leak | 19 | 12 | 2 | 39.1 | 10.65 | 17 | 11 | 4 | 37.1 | 10.17 | 10 | 1 | 4 | 6.4 | 1.70 |
| Load | 1 | 4 | 4 | 14.5 | 3.95 | 1 | 4 | 2 | 13.3 | 3.65 | 12 | 4 | 10 | 19.2 | 5.10 |
| Coil | 2 | 12 | 3 | 38 | 10.35 | 1 | 4 | 0 | 12.1 | 3.32 | 5 | 4 | 4 | 14.9 | 3.96 |
| | | | | 367 | | | | | 364.7 | | | | | 376.5 | |

Table G.2; System 1 (office) component sensitivity correlation with system capacity changes

| Capacity | Chiller age | Chiller | Supply Fan | Supply Fan age | Return Fan | Return Fan age | Cooling Tower | Cooling Tower age | |
|---|---|---|---|---|---|---|---|---|---|
| 150 | 10.44 | 8.07 | 3.68 | 2.18 | 1.25 | 5.75 | 5.42 | 2.51 | |
| 300 | 2.3 | 9.6 | 12.06 | 1.21 | 8.69 | 5.79 | 3.15 | 5.02 | |
| 450 | 3.69 | 3.03 | 4.49 | 5.82 | 2.76 | 10.81 | 10.97 | 3.35 | |
| corr. | -0.78 | -0.73 | 0.09 | 0.75 | 0.19 | 0.87 | 0.69 | 0.33 | |
| Capacity | CHWP | CHWP age | CWP | CWP age | TU | TU age | Load | Leak | Coil |
| 150 | 8.39 | 8.5 | 3.13 | 6.95 | 3.41 | 5.37 | 3.95 | 10.65 | 10.35 |
| 300 | 5.02 | 9.13 | 6.36 | 4.77 | 4.36 | 5.4 | 3.65 | 10.17 | 3.32 |
| 450 | 11.85 | 13.09 | 2.26 | 8.21 | 6.85 | 2.07 | 5.1 | 1.7 | 3.96 |
| corr. | 0.51 | 0.92 | -0.20 | 0.36 | 0.97 | -0.86 | 0.75 | -0.89 | -0.82 |

Table G.3; System 2 (office) component sensitivity with system capacity changes

| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 150 Tons | | | | | 300 Tons | | | | | 450 Tons | | | | |
| System 2 | 25 | 50 | 75 | Average | % | 25 | 50 | 75 | Average | % | 25 | 50 | 75 | Average | % |
| Compressor | 8 | 19 | 15 | 66.8 | 17.91 | 19 | 16 | 4 | 52.3 | 14.22 | 8 | 13 | 16 | 49.4 | 13.45 |
| Compressor age | 2 | 8 | 5 | 27.2 | 7.29 | 11 | 1 | 2 | 5.3 | 1.44 | 7 | 11 | 0 | 33.7 | 9.18 |
| Supply Fan | 6 | 3 | 0 | 9.6 | 2.57 | 8 | 9 | 10 | 33.8 | 9.19 | 2 | 6 | 18 | 29 | 7.90 |
| Supply Fan age | 7 | 1 | 8 | 8.5 | 2.28 | 4 | 10 | 4 | 32.8 | 8.92 | 3 | 12 | 4 | 38.7 | 10.54 |
| Return Fan | 6 | 10 | 5 | 33.6 | 9.01 | 1 | 1 | 12 | 10.3 | 2.80 | 4 | 6 | 1 | 19 | 5.17 |
| Return Fan age | 10 | 3 | 12 | 17.2 | 4.61 | 5 | 6 | 2 | 19.7 | 5.36 | 5 | 4 | 6 | 16.1 | 4.38 |
| Condenser Fan | 10 | 6 | 6 | 22.6 | 6.06 | 9 | 1 | 12 | 11.1 | 3.02 | 5 | 1 | 12 | 10.7 | 2.91 |
| Condenser Fan age | 8 | 8 | 1 | 25.4 | 6.81 | 3 | 2 | 9 | 11.7 | 3.18 | 4 | 6 | 6 | 22 | 5.99 |
| Chilled Water Pump | 10 | 5 | 6 | 19.6 | 5.26 | 11 | 0 | 11 | 7.7 | 2.09 | 12 | 9 | 16 | 37.8 | 10.29 |
| Chilled Water Pump age | 1 | 5 | 7 | 19.3 | 5.18 | 11 | 11 | 6 | 37.7 | 10.25 | 9 | 5 | 6 | 19.5 | 5.31 |
| Terminal Unit | 6 | 12 | 9 | 42 | 11.26 | 4 | 10 | 9 | 35.8 | 9.73 | 1 | 5 | 1 | 15.7 | 4.28 |
| Terminal Unit age | 6 | 3 | 6 | 13.2 | 3.54 | 7 | 5 | 3 | 17.5 | 4.76 | 6 | 9 | 4 | 30 | 8.17 |
| Leak | 5 | 1 | 13 | 11.3 | 3.03 | 1 | 4 | 6 | 15.7 | 4.27 | 10 | 2 | 8 | 11.8 | 3.21 |
| Load | 2 | 9 | 6 | 30.8 | 8.26 | 3 | 15 | 5 | 48.3 | 13.13 | 3 | 3 | 0 | 9.3 | 2.53 |
| Coil | 12 | 8 | 1 | 25.8 | 6.92 | 5 | 8 | 6 | 28.1 | 7.64 | 23 | 7 | 2 | 24.5 | 6.67 |
| | | | | 372.9 | | | | | 367.8 | | | | | 367.2 | |

Table G.4; System 2 (office) component sensitivity correlation with system capacity changes

| Capacity | Compressor | Comp. Age | Supply Fan | Supply Fan age | Return Fan | Return Fan age | Condenser Fan | Condenser Fan age |
|---|---|---|---|---|---|---|---|---|
| 150 | 17.91 | 7.29 | 2.57 | 2.28 | 9.01 | 4.61 | 6.06 | 6.81 |
| 300 | 14.22 | 1.44 | 9.19 | 8.92 | 2.8 | 5.36 | 3.02 | 3.18 |
| 450 | 13.45 | 9.18 | 7.9 | 10.54 | 5.17 | 4.38 | 2.91 | 5.99 |
| corr. | -0.94 | 0.23 | 0.76 | 0.94 | -0.61 | -0.22 | -0.88 | -0.22 |
| Capacity | CHWP | CHWP age | TU | TU age | Load | Leak | Coil | |
| 150 | 5.26 | 5.18 | 11.26 | 3.54 | 8.26 | 3.03 | 6.92 | |
| 300 | 2.09 | 10.25 | 9.37 | 4.76 | 13.13 | 4.27 | 7.64 | |
| 450 | 10.29 | 5.31 | 4.28 | 8.17 | 2.53 | 3.21 | 6.67 | |
| corr. | 0.61 | 0.02 | -0.97 | 0.96 | -0.54 | 0.13 | -0.25 | |

Table G.5; System 3 (office) component sensitivity with system capacity changes

| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 150 Tons | | | | | 300 Tons | | | | | 450 Tons | | | | |
| System 3 | 25 | 50 | 75 | Average | % | 25 | 50 | 75 | Average | % | 25 | 50 | 75 | Average | % |
| Compressor | 4 | 28 | 74 | 128.8 | 34.59 | 4 | 31 | 47 | 121.6 | 32.60 | 6 | 16 | 80 | 96.6 | 25.95 |
| Compressor age | 5 | 3 | 0 | 9.5 | 2.55 | 4 | 5 | 0 | 15.4 | 4.13 | 7 | 10 | 2 | 31.9 | 8.57 |
| Supply Fan | 16 | 1 | 3 | 6.4 | 1.72 | 20 | 8 | 1 | 26.6 | 7.13 | 9 | 8 | 1 | 25.5 | 6.85 |
| Supply Fan age | 15 | 19 | 4 | 60.9 | 16.35 | 6 | 1 | 1 | 4.2 | 1.13 | 3 | 9 | 2 | 28.5 | 7.66 |
| Return Fan | 10 | 3 | 4 | 12.4 | 3.33 | 11 | 16 | 0 | 49.1 | 13.16 | 7 | 2 | 2 | 7.9 | 2.12 |
| Return Fan age | 12 | 2 | 4 | 9.6 | 2.58 | 1 | 4 | 1 | 12.7 | 3.40 | 8 | 5 | 0 | 15.8 | 4.24 |
| Condenser Fan | 2 | 5 | 2 | 16.4 | 4.40 | 2 | 1 | 47 | 31.4 | 8.42 | 5 | 20 | 2 | 61.7 | 16.57 |
| Condenser Fan age | 5 | 8 | 3 | 26.3 | 7.06 | 13 | 8 | 0 | 25.3 | 6.78 | 11 | 0 | 2 | 2.3 | 0.62 |
| Terminal Unit | 8 | 2 | 2 | 8 | 2.15 | 2 | 4 | 1 | 12.8 | 3.43 | 12 | 3 | 4 | 12.6 | 3.38 |
| Terminal Unit age | 4 | 16 | 0 | 48.4 | 13.00 | 0 | 8 | 0 | 24 | 6.43 | 4 | 3 | 1 | 10 | 2.69 |
| Leak | 5 | 2 | 0 | 6.5 | 1.75 | 13 | 3 | 1 | 10.9 | 2.92 | 4 | 3 | 2 | 10.6 | 2.85 |
| Load | 3 | 1 | 2 | 4.5 | 1.21 | 10 | 9 | 0 | 28 | 7.51 | 13 | 5 | 1 | 16.9 | 4.54 |
| Coil | 11 | 11 | 1 | 34.7 | 9.32 | 14 | 3 | 1 | 11 | 2.95 | 10 | 17 | 0 | 52 | 13.97 |
| | | | | 372.4 | | | | | 373 | | | | | 372.3 | |

Table G.6; System 3 (office) component sensitivity correlation with system capacity changes

| Capacity | Compressor | Comp. Age | Supply Fan | Supply Fan age | Return Fan | Return Fan age | Condenser Fan | Condenser Fan age |
|---|---|---|---|---|---|---|---|---|
| 150 | 34.59 | 2.55 | 1.72 | 16.35 | 3.33 | 2.58 | 4.4 | 7.06 |
| 300 | 32.6 | 4.13 | 7.13 | 1.13 | 13.16 | 3.4 | 8.42 | 6.78 |
| 450 | 25.95 | 8.57 | 6.85 | 7.66 | 2.12 | 4.24 | 16.57 | 0.62 |
| corr. | -0.95 | 0.96 | 0.84 | -0.57 | -0.10 | 1.00 | 1.00 | -0.98 |
| Capacity | TU | TU age | Load | Leak | Coil | | | |
| 150 | 2.15 | 13 | 1.21 | 1.75 | 9.32 | | | |
| 300 | 3.43 | 6.43 | 7.51 | 2.92 | 2.95 | | | |
| 450 | 3.38 | 2.69 | 4.54 | 2.85 | 6.67 | | | |
| corr. | 0.85 | -0.99 | 0.53 | 0.84 | -0.41 | | | |

Table G.7; System 4 (office) component sensitivity with system capacity changes

| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 150 Tons | | | | | 300 Tons | | | | | 450 Tons | | | | |
| System 4 | 25 | 50 | 75 | Average | % | 25 | 50 | 75 | Average | % | 25 | 50 | 75 | Average | % |
| Compressor | 0 | 28 | 1 | 84.6 | 22.69 | 3 | 12 | 2 | 37.5 | 10.12 | 12 | 14 | 5 | 46.2 | 12.54 |
| Compressor age | 6 | 6 | 0 | 18.6 | 4.99 | 12 | 9 | 10 | 34.2 | 9.23 | 0 | 12 | 3 | 37.8 | 10.26 |
| Supply Fan | 10 | 5 | 11 | 22.6 | 6.06 | 11 | 12 | 6 | 40.7 | 10.98 | 9 | 5 | 3 | 17.7 | 4.80 |
| Supply Fan age | 14 | 0 | 4 | 3.8 | 1.02 | 1 | 3 | 5 | 12.1 | 3.26 | 12 | 7 | 9 | 27.6 | 7.49 |
| Return Fan | 1 | 8 | 20 | 36.1 | 9.68 | 6 | 0 | 15 | 9.6 | 2.59 | 1 | 3 | 12 | 16.3 | 4.42 |
| Return Fan age | 1 | 3 | 11 | 15.7 | 4.21 | 6 | 3 | 2 | 10.8 | 2.91 | 7 | 1 | 13 | 11.5 | 3.12 |
| Condenser Fan | 15 | 4 | 0 | 13.5 | 3.62 | 1 | 2 | 14 | 14.5 | 3.91 | 11 | 7 | 11 | 28.7 | 7.79 |
| Condenser Fan age | 3 | 7 | 2 | 22.5 | 6.03 | 1 | 2 | 2 | 7.3 | 1.97 | 4 | 7 | 5 | 24.4 | 6.62 |
| Condenser water Pump | 2 | 4 | 1 | 12.8 | 3.43 | 12 | 1 | 5 | 7.2 | 1.94 | 11 | 5 | 5 | 19.1 | 5.18 |
| Condenser Water Pump a | 3 | 8 | 9 | 29.7 | 7.96 | 11 | 15 | 7 | 50.3 | 13.57 | 2 | 5 | 10 | 21.2 | 5.75 |
| Terminal Unit | 15 | 0 | 3 | 3.3 | 0.88 | 11 | 1 | 3 | 5.9 | 1.59 | 11 | 9 | 1 | 28.7 | 7.79 |
| Terminal Unit age | 18 | 10 | 10 | 37.8 | 10.14 | 13 | 7 | 3 | 24.1 | 6.50 | 13 | 3 | 0 | 10.3 | 2.80 |
| Leak | 2 | 8 | 3 | 26 | 6.97 | 1 | 15 | 2 | 46.3 | 12.49 | 3 | 7 | 8 | 26.1 | 7.08 |
| Load | 5 | 2 | 20 | 18.5 | 4.96 | 4 | 9 | 22 | 40.6 | 10.96 | 2 | 4 | 10 | 18.2 | 4.94 |
| Coil | 4 | 8 | 5 | 27.4 | 7.35 | 7 | 9 | 3 | 29.5 | 7.96 | 4 | 10 | 7 | 34.6 | 9.39 |
| | | | | 372.9 | | | | | 370.6 | | | | | 368.4 | |

Table G.8; System 4 (office) component sensitivity correlation with system capacity changes

| Capacity | Compressor | Comp. Age | Supply Fan | Supply Fan age | Return Fan | Return Fan age | Condenser Fan | Condenser Fan age |
|---|---|---|---|---|---|---|---|---|
| 150 | 22.69 | 4.99 | 6.06 | 1.02 | 9.68 | 4.21 | 3.62 | 6.03 |
| 300 | 10.12 | 9.23 | 10.98 | 3.26 | 2.59 | 2.91 | 3.91 | 1.97 |
| 450 | 12.54 | 10.26 | 4.8 | 7.49 | 4.42 | 3.12 | 7.79 | 6.62 |
| corr. | -0.76 | 0.94 | -0.19 | 0.98 | -0.71 | -0.78 | 0.70 | -0.22 |
| Capacity | TU | TU age | Load | Leak | Coil | | | |
| 150 | 0.88 | 10.14 | 4.96 | 6.97 | 7.35 | | | |
| 300 | 1.59 | 6.5 | 10.96 | 12.49 | 7.96 | | | |
| 450 | 7.79 | 2.8 | 4.49 | 7.08 | 9.39 | | | |
| corr. | 0.91 | -1.00 | -0.07 | 0.02 | 0.97 | | | |

Table G.9; System 5 (office) component sensitivity with system capacity changes

| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 150 Tons | | | | | 300 Tons | | | | | 450 Tons | | | | |
| System 5 | 25 | 50 | 75 | Average | % | 25 | 50 | 75 | Average | % | 25 | 50 | 75 | Average | % |
| Chiller | 3 | 8 | 3 | 26.1 | 7.10 | 9 | 6 | 4 | 21.3 | 5.69 | 7 | 6 | 3 | 20.5 | 5.55 |
| Chiller age | 7 | 0 | 4 | 3.1 | 0.84 | 0 | 8 | 1 | 24.6 | 6.57 | 9 | 7 | 11 | 28.5 | 7.72 |
| Supply Fan | 7 | 0 | 1 | 1.3 | 0.35 | 17 | 0 | 1 | 2.3 | 0.61 | 10 | 7 | 1 | 22.6 | 6.12 |
| Supply Fan age | 10 | 5 | 14 | 24.4 | 6.64 | 1 | 6 | 14 | 26.5 | 7.07 | 11 | 5 | 5 | 19.1 | 5.17 |
| Return Fan | 2 | 7 | 1 | 21.8 | 5.93 | 1 | 1 | 15 | 12.1 | 3.23 | 10 | 8 | 6 | 28.6 | 7.74 |
| Return Fan age | 0 | 7 | 7 | 25.2 | 6.86 | 2 | 1 | 14 | 11.6 | 3.10 | 3 | 2 | 16 | 15.9 | 4.30 |
| Cooling Tower | 1 | 5 | 10 | 21.1 | 5.74 | 9 | 10 | 1 | 31.5 | 8.41 | 1 | 10 | 0 | 30.1 | 8.15 |
| Cooling Tower age | 7 | 6 | 3 | 20.5 | 5.58 | 0 | 9 | 1 | 27.6 | 7.37 | 11 | 10 | 15 | 40.1 | 10.86 |
| Chilled Water Pump | 0 | 7 | 0 | 21 | 5.71 | 8 | 13 | 1 | 40.4 | 10.78 | 1 | 12 | 16 | 45.7 | 12.37 |
| Chilled Water Pump age | 9 | 6 | 14 | 27.3 | 7.43 | 10 | 4 | 4 | 15.4 | 4.11 | 4 | 4 | 1 | 13 | 3.52 |
| Condenser Water Pump | 2 | 6 | 15 | 27.2 | 7.40 | 2 | 6 | 7 | 22.4 | 5.98 | 3 | 5 | 5 | 18.3 | 4.95 |
| Condenser Water Pump a | 7 | 1 | 5 | 6.7 | 1.82 | 7 | 4 | 8 | 17.5 | 4.67 | 8 | 4 | 2 | 14 | 3.79 |
| Fan Coil Unit | 5 | 3 | 8 | 14.3 | 3.89 | 6 | 1 | 8 | 8.4 | 2.24 | 2 | 10 | 3 | 32 | 8.66 |
| Fan Coil Unit age | 16 | 7 | 11 | 29.2 | 7.94 | 0 | 14 | 10 | 48 | 12.81 | 0 | 4 | 7 | 16.2 | 4.39 |
| Leak | 8 | 14 | 1 | 43.4 | 11.81 | 0 | 0 | 5 | 3 | 0.80 | 0 | 3 | 4 | 11.4 | 3.09 |
| Load | 8 | 3 | 4 | 12.2 | 3.32 | 9 | 4 | 1 | 13.5 | 3.60 | 20 | 3 | 0 | 11 | 2.98 |
| Coil | 8 | 14 | 0 | 42.8 | 11.64 | 17 | 14 | 8 | 48.5 | 12.95 | 0 | 0 | 4 | 2.4 | 0.65 |
| | | | | 367.6 | | | | | 374.6 | | | | | 369.4 | |

Table G.10; System 5 (office) component sensitivity correlation with system capacity changes

| Capacity | Chiller age | Chiller | Supply Fan | Supply Fan age | Return Fan | Return Fan age | Cooling Tower | Cooling Tower age | |
|---|---|---|---|---|---|---|---|---|---|
| 150 | 0.84 | 7.1 | 0.35 | 6.64 | 5.93 | 6.86 | 5.74 | 5.58 | |
| 300 | 6.57 | 5.69 | 0.61 | 7.07 | 3.23 | 3.1 | 8.41 | 7.37 | |
| 450 | 7.72 | 5.55 | 6.12 | 5.17 | 7.74 | 4.3 | 8.15 | 10.86 | |
| corr. | 0.93 | -0.90 | 0.89 | -0.74 | 0.40 | -0.67 | 0.82 | 0.98 | |
| Capacity | CHWP | CHWP age | CWP | CWP age | FCU | FCU age | Load | Leak | Coil |
| 150 | 5.71 | 7.43 | 7.4 | 1.82 | 3.89 | 7.94 | 3.32 | 11.81 | 11.64 |
| 300 | 10.78 | 4.11 | 5.98 | 4.67 | 2.24 | 12.81 | 3.6 | 0.8 | 12.95 |
| 450 | 12.37 | 3.52 | 4.95 | 3.79 | 8.66 | 4.39 | 2.98 | 3.09 | 0.65 |
| corr. | 0.96 | -0.93 | -1.00 | 0.67 | 0.72 | -0.42 | -0.55 | -0.75 | -0.81 |

Table G.11; System 6 (office) component sensitivity with system capacity changes

| | 150 Tons | | | | | 300 Tons | | | | | 450 Tons | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| System 6 | 25 | 50 | 75 | Average | % | 25 | 50 | 75 | Average | % | 25 | 50 | 75 | Average | % |
| Chiller | 12 | 10 | 22 | 44.4 | 12.18 | 7 | 4 | 22 | 25.9 | 7.06 | 3 | 15 | 20 | 57.3 | 15.72 |
| Chiller age | 13 | 11 | 8 | 39.1 | 10.72 | 9 | 4 | 0 | 12.9 | 3.51 | 0 | 7 | 4 | 23.4 | 6.42 |
| Supply Fan | 3 | 0 | 5 | 3.3 | 0.91 | 1 | 9 | 3 | 28.9 | 7.87 | 12 | 8 | 0 | 25.2 | 6.91 |
| Supply Fan age | 2 | 6 | 2 | 19.4 | 5.32 | 0 | 1 | 0 | 3 | 0.82 | 12 | 5 | 3 | 18 | 4.94 |
| Return Fan | 13 | 13 | 8 | 45.1 | 12.37 | 8 | 3 | 2 | 11 | 3.00 | 17 | 11 | 6 | 38.3 | 10.51 |
| Return Fan age | 0 | 0 | 13 | 7.8 | 2.14 | 9 | 11 | 6 | 37.5 | 10.22 | 0 | 2 | 9 | 11.4 | 3.13 |
| Condenser Fan | 8 | 13 | 5 | 42.8 | 11.74 | 10 | 5 | 11 | 22.6 | 6.16 | 18 | 11 | 5 | 37.8 | 10.37 |
| Condenser Fan age | 16 | 0 | 1 | 2.2 | 0.60 | 4 | 4 | 4 | 14.8 | 4.03 | 1 | 5 | 4 | 17.5 | 4.80 |
| Chilled Water Pump | 0 | 6 | 3 | 19.8 | 5.43 | 13 | 10 | 7 | 35.5 | 9.67 | 1 | 0 | 6 | 3.7 | 1.02 |
| Chilled Water Pump age | 0 | 5 | 13 | 22.8 | 6.25 | 8 | 12 | 7 | 41 | 11.17 | 12 | 5 | 1 | 16.8 | 4.61 |
| Fan Coil Unit | 5 | 10 | 5 | 33.5 | 9.19 | 6 | 16 | 12 | 55.8 | 15.20 | 5 | 13 | 2 | 40.7 | 11.17 |
| Fan Coil Unit age | 6 | 1 | 1 | 4.2 | 1.15 | 4 | 13 | 4 | 41.8 | 11.39 | 1 | 1 | 9 | 8.5 | 2.33 |
| Leak | 13 | 16 | 12 | 56.5 | 15.50 | 18 | 3 | 6 | 14.4 | 3.92 | 3 | 5 | 8 | 20.1 | 5.51 |
| Load | 3 | 7 | 1 | 21.9 | 6.01 | 0 | 0 | 5 | 3 | 0.82 | 14 | 0 | 10 | 7.4 | 2.03 |
| Coil | 6 | 0 | 2 | 1.8 | 0.49 | 3 | 4 | 11 | 18.9 | 5.15 | 0 | 10 | 14 | 38.4 | 10.53 |
| | | | | 364.6 | | | | | 367 | | | | | 364.5 | |

Table G.12; System 6 (office) component sensitivity correlation with system capacity changes

| Capacity | Compressor | Comp. Age | Supply Fan | Supply Fan age | Return Fan | Return Fan age | Condenser Fan | Condenser Fan age |
|---|---|---|---|---|---|---|---|---|
| 150 | 12.18 | 10.72 | 0.91 | 5.32 | 12.37 | 2.14 | 11.74 | 0.6 |
| 300 | 7.06 | 3.51 | 7.87 | 0.82 | 3 | 10.22 | 6.16 | 4.03 |
| 450 | 15.72 | 6.42 | 6.91 | 4.94 | 10.51 | 3.13 | 10.37 | 4.8 |
| corr. | 0.41 | -0.59 | 0.80 | -0.08 | -0.19 | 0.11 | -0.24 | 0.94 |
| Capacity | CHWP | CHWP age | FCU | FCU age | Load | Leak | Coil | |
| 150 | 5.43 | 9.19 | 9.19 | 1.15 | 6.01 | 15.5 | 0.49 | |
| 300 | 9.67 | 15.2 | 15.2 | 11.39 | 0.82 | 3.92 | 5.15 | |
| 450 | 1.02 | 11.17 | 11.17 | 2.33 | 2.03 | 5.51 | 10.53 | |
| corr. | -0.51 | 0.32 | 0.32 | 0.11 | -0.73 | -0.80 | 1.00 | |

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